BURNING QUESTIONS: A GEOSPATIAL ANALYSIS OF FIRE REGIME CHANGE IN CÔTE D'IVOIRE, 1984-2014

BY

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THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Geography
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2015

Urbana, Illinois

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ABSTRACT

Africa has been called the “burn center” of the planet because it is the continent where the greatest proportion of global fire occurs. This widespread yet poorly understood phenomenon holds the key to processes such as land cover change, vegetation change, and the emission of greenhouse gasses. To understand this role, better information about the distribution and drivers of fire is needed. Research in West Africa points to seasonal changes in vegetation burning over the past 30 years. In Côte d’Ivoire, fieldwork at the *terroir* scale in one savanna region indicates an increase in the proportion of early dry season fires related to the expansion of livestock raising. Since early dry season fires are generally less intense than late dry season fires, a shift toward early season burning will influence vegetation cover and greenhouse gas emissions. But are these shifts apparent at broader scales? How does cattle herding interact with other variables affecting fire?

This research investigates the factors affecting fire seasonality at the country level in Côte d’Ivoire. I reconstruct a representative history of fire activity for Côte d’Ivoire using more than 5000 Landsat TM/ETM+ images over the period 1984 to 2014. Active fires are detected in each image using two indices based on the radiance of fire in the shortwave infrared portion of the electromagnetic spectrum. The work assesses the fire regime as represented by active fire in 896 locations covering Côte d’Ivoire. It also investigates the relationship of fire patterns with climate and land use/land cover variables using random forest regression. The independent variables show a strong relationship with fire regularity and a weaker, though important, relationship with timing and density of fires.

The results reveal spatial and temporal patterns in fire seasonality over the past 30 years in Côte d’Ivoire. While I conclude that the timing of fire across Côte d’Ivoire has not shown a substantial linear trend over time, the seasonality, density, and regularity of fire has fluctuated over time and space. These variations are related to temperature, rainfall, and pastoralism, among other variables. Improving

the understanding of fire regimes in Côte d'Ivoire can shed new light on ongoing debates regarding the impacts of increasing agricultural activity in West Africa on fire, vegetation, and climate change.

ACKNOWLEDGEMENTS

I would like to acknowledge all those who helped bring this thesis work to completion. Special thanks are due to my advisors, Dr. Jonathan Greenberg and Dr. Thomas Bassett, who provided much of the inspiration and guidance that were needed to make my thesis a reality. Their patience and willingness to work between the worlds of political ecology, remote sensing, and fire kept this project moving forward. I would also like to thank Dr. Trevor Birkenholtz for his contributions as the third member of my thesis committee. Finally, Stephanie Mundis, Jiangdong Liu, and Alejandra Restrepo were very helpful in preparing and validating a portion of the data that went into my research.

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Chapter 1. Introduction

Fire is a significant component of the savanna systems of West Africa, with over 50% of the total land area set alight each year in some regions (Laris, 2005). The patterns of burning in this region are believed to be highly influenced by humans (Bassett, Koli Bi, and Ouattara, 2003; Laris, 2013). People use fire as a tool for the management of agricultural lands, for hunting, and for the creation of fire breaks (Bowman et al., 2011). However, when the characteristics of fire change, burning can also act as a driver of ecological change. The seasonal timing of annual fires plays a significant role in determining the balance between fire's role in sustainable management and land cover change. Early dry season fires generally result in lower intensity burns, lower emission of greenhouse gases, and a greater cover of woody vegetation (Bond and van Wilgen, 1996; Koné, Bassett, and Nkem, 2011). Local-scale studies of savanna systems in Côte d'Ivoire show that fire seasonality has shifted over the past 30 years, signaling potentially important changes in land use and land cover (Koné et al., 2011).

The seasonality of fire represents one important aspect of the pattern of fire's occurrence across a landscape, or the fire regime (Gill, 1975). Previous studies have examined aspects of the fire regimes of West Africa at the global (Giglio, Csiszar, and Justice, 2006), continental (Archibald, Scholes, Roy, Roberts, and Boschetti, 2010; Cooke, Koffi, and Grégoire, 1996), and local scales (Bassett et al., 2003; Laris, 2011). These studies, however, do not capture the full variability of fire regimes and, in some cases, lack the ability to explain the patterns observed. Understanding the potential role of fire in land cover change and climate change requires better characterization of these aspects of fire across broad spatial and temporal scales. Such information could guide policy and management toward improved social and ecological outcomes.

The factors that determine the fire regimes in Africa are currently debated, with primary candidates related to either climate or human activity. As interest in the impacts of land use on the climate system increase, understanding these drivers is becoming more important. Greater information is needed to inform attempts to mitigate climate change through land management. At the same time, agricultural activity is known to be intensifying in West Africa (Andela and van der Werf, 2014), a trend that may also be driving changes in fire activity. These new developments underline the importance of better knowledge about the variables controlling fire in West Africa.

Using a historical archive of remote sensing imagery covering the period of 1984-2014 across Côte d'Ivoire, the research presented here investigates patterns of active fire in Côte d'Ivoire over time and space. I ask: What patterns in fire activity over time and space are visible in Côte d'Ivoire? How do climate and human activity relate to these patterns? To answer these questions, I use active fire detection to examine three aspects of fire activity in Côte d'Ivoire: the density of fires, the timing of peak fire, and the regularity with which fire burns over time.

Chapter 2. Literature Review

2.1 Fire, Ecology & Society

Fire is an ephemeral phenomenon, a meeting of fuel, oxygen, and spark. Thus, fire is best understood as a reaction, a process of change, rather than an entity in and of itself. Defining the role of fire in a landscape is complicated by its transitory nature. Burns in one year may differ vastly from those in the past year, decade, or even century. Nevertheless, patterns emerge. The characteristics of fire in a particular landscape are known as the fire regime (Gill, 1975). The fire regime describes the intensity, severity, frequency, seasonality, fuel consumption, and fire spread (Bond and Keeley, 2005). These terms are defined in table 1.

Fire has been a component of terrestrial systems since the emergence of vegetation on land during the Silurian period about 420 Ma (Bowman et al., 2009; Scott, 2000, 2010). Large deposits of charcoal during the Permian suggest that fire was an especially prominent feature of the Earth system when atmospheric oxygen exceeded 30% approximately 250-300 Ma (Scott and Glasspool, 2006). More recently, fire is believed to have played a role in the expansion of tropical savannas about 7 to 8 Ma (Jacobs, Kingston, and Jacobs, 1999). While this shift was probably primed by declining atmospheric CO_2, fire played the dominant role in this expansion (Beerling and Osborne, 2006). Globally, the remarkable stability and extent of savannas was reinforced by feedback mechanisms among fire, climate and vegetation (Beerling and Osborne, 2006).

Fires are presently an important component of many ecosystems on every populated continent. Available estimates suggest that approximately 200-600 million hectares burn each year around the world (Hoelzemann, 2004; Mouillot and Field, 2005). Where they are common, fires are necessary for the sustainability of ecosystems. Fire exclusion and suppression cause substantial changes in vegetation structure in such systems (Bond and van Wilgen, 1996). Fires are especially important in savanna ecosystems, where fire is thought to be a key factor in maintaining the balance between grasses and tree cover (Bond and van Wilgen, 1996; Bond, Woodward, and Midgley, 2005). Newer models of grass-tree interaction further suggest that the regular presence of fire disturbance is necessary to explain the global distribution of savannas (Lehmann, Archibald, Hoffmann, and Bond, 2011).

A limitation of many studies examining the global distribution of fire is the lack of attention paid to human activity. This is surprising given that the most recent increase in global fire occurrence coincided with human migrations to Europe, Asia, Australia, and the Americas (Bowman et al., 2009). Today, human activities dominate many landscape characteristics, fire among them. The impact of humans is therefore of critical importance to understanding the nature of fire in the Earth system.

Fire has played an important role in the lives of people for millennia. While intense debate exists over the possible evolutionary origins of humans in a landscape dominated by fire (Domínguez-Rodrigo, 2014), we know that humans have made regular domestic use of fire for at least 50,000 to 100,000 years (Bar-Yosef, 2002), and possibly as much as 1.9 million years (Wrangham, Jones, Laden, Pilbeam, and Conklin-Brittain, 1999). Human management of landscape fire is diverse, widespread, and long-practiced as well (Bowman et al., 2009; Eriksen, 2007). Indeed, the concordance between the spread of humans and the prevalence of fire historically (Bowman et al., 2009; Thevenon, Bard, Williamson, and Beaufort, 2004) suggests that humans have used and promoted fire-affected landscapes for tens of thousands of years, if not longer. Archibald, Staver, & Levin (2012) argue that humans could have affected fire regimes in Africa as much as 1.5 Ma through the modification of fires initially ignited by lightning. That impact would have increased as humans gained the ability to ignite fires independently of lightning and manipulate the landscape at large scales over 300,000 years ago.

Today, it is estimated that humans are responsible for about 90% of all fire ignitions (Levine, Cofer, Cahoon, and Winstead, 1995), with the remainder largely attributable to lightning strikes. In areas where fire suppression has been the dominant fire management paradigm, such as the United States, human ignitions account for the largest proportion of fire ignitions but are largely accidental (Pyne, 1984). In other areas, however, fire is a tool utilized by people to achieve land management goals efficiently. In Africa, fire is used for rangeland management, preparation of crop fields, hunting, security from theft, and protection against more intense fires (Eriksen, 2007; Fairhead and Leach, 1995; Kull and Laris, 2009; Laris and Wardell, 2006; Laris, 2002, 2013; Mbow, Nielsen, and Rasmussen, 2000).

In fact, humans have made use of landscape fire on every vegetated continent in some way. Humans are able to influence the fire regime by altering environmental conditions and through direct ignition of fires. Variables open to human influence include fuel characteristics including load, moisture, and continuity and wind speed through landscape modification (Bowman et al., 2011) as well as timing of ignition. Despite its widespread occurrence, the use of fire in landscape management remains controversial in many places, not least because fire can easily escape human control, transforming from tool to disaster. There has been a strong tendency in European and academic traditions and policy to emphasize the negative impacts of fire (Bassett et al., 2003; Caillault, Ballouche, and Delahaye, 2014; Kull, 2004) despite indications that fire can not only be a sustainable but necessary component in some systems (Bowman et al., 2009, 2011; Pyne, 2009).

In recent decades, a new concern has arisen regarding the impact of human use of fire: the potential contribution to anthropogenic climate change (Meinrat O. Andreae, 1991). The combustion of biomass releases various climate-relevant gasses, and fire can contribute to deforestation and net carbon release, as has been documented in the Amazon (Cochrane et al., 1999) and South East Asia (Miettinen, Shi, and Liew, 2011). The advent of concerns that biomass burning could contribute to climate change motivated forceful recommendations to limit biomass burning (Andrasko, Ahuja, Winnett, and Tirpak, 1991). Recently, the potential use of fire in carbon sequestration has also garnered significant attention (Bradstock et al., 2012; Neely, Bunning, and Wilkes, 2009; Wiedinmyer and

Hurteau, 2010; Woodfine, 2009). The following section reviews potential connections between fire and the climate system.

2.2 Biomass Burning and Climate Change

As a major driver of carbon fluxes, as a source of various trace gases and aerosols, and as a determinant of vegetation characteristics and a driver of land cover change, biomass burning has the potential to significantly influence the climate system. Understanding the effects of biomass burning is important for accurate modeling of global climate change, forecasting of fire hazards, and policy planning for climate change mitigation and disaster prevention. The nature of fire's influence is difficult to assess, however, due to the complex and event specific nature of fire. Here, I review the current understanding of biomass burning's roles and impacts within the climate system. I give particular attention to the available sources of information from which fire's impacts are determined and to the existing difficulties in attempts to characterize those impacts.

2.2.1 Role of burning in chemical processes and climate forcings

The IPCC defines biomass burning as "the burning of living and dead vegetation" (Allwood, Bosetti, Dubash, Gómez-Echeverri, and Stech, 2014). Biomass burning refers to the burning of vegetation in savannas and forests, as well as the burning of domestic fuels, agricultural wastes, and charcoal (Meinrat O. Andreae, 1991; Delmas, Loudjani, Podaire, and Menaut, 1991; Liousse et al., 2004). Biomass burning is a feature of most landscapes globally, though the distribution is uneven.

A change in the physical or chemical characteristics of the earth system that results in a shift in the climate equilibrium is known as a climate forcing. Climate change can occur via either direct or indirect effects of a particular climate forcing (Hartmann, 1994). Direct effects refer to the direct interaction of a particle or surface with radiation, resulting in a change in Earth's radiative balance. Indirect effects occur when a species influences other climate processes which themselves influence climate. CO_2, trace gasses, water vapor, and particulates released from fire influence the climate system.

These emissions have both direct and indirect impacts on climate (Meinrat O. Andreae and Merlet, 2001; Crutzen and Andreae, 1990; Crutzen, Heidt, and Krasnec, 1979). In addition, biomass burning indirectly effects the climate system through changes in vegetation, with short- and long-term changes in albedo (Beringer et al., 2003), carbon stored in biomass (Balshi et al., 2009), and cloud formation (M O Andreae et al., 2004).

Worldwide biomass burning has been estimated to contribute as much as 40% of the bulk emissions of carbon dioxide globally (Meinrat O. Andreae, 1991), an amount that is within an order of magnitude of emissions from fossil fuel burning. However, the role of these emissions in climate change is complicated by the fact that much of the CO_2 released by fire is balanced by vegetation regrowth over time (Bowman et al., 2009). In general, biomass burning is considered to be in an equilibrium state with the climate except where fire results in land cover change, especially in the case of fire's use for deforestation. However, because interannual variability of burned area is high, fire is believed to be the greatest driver of variability in the rate of CO_2 increase in the atmosphere (van der Werf et al., 2006). Fire is thus an important component of the global carbon cycle but not necessarily a contributor to climate change as a result of CO_2 emissions.

Aside from carbon dioxide, biomass burning is a significant source of dozens of trace gases including methane, CO, NOx, ammonia, VOC, carbonyl sulfide, and sulfur dioxide (Meinrat O. Andreae and Merlet, 2001). These emissions can exert climate forcings in various ways. For instance, methane released from fires acts directly as a greenhouse gas. However, aerosols from fire are expected to result in negative forcing on the climate system (Sena, Artaxo, and Correia, 2013). Modification of surface albedo due to fire can act as a climate forcing as well. Although the evolution of black materials from fire is expected to reduce surface albedo for several weeks after a fire (IPCC, 2007), the long term effects of fire on albedo are positive, resulting in negative climate forcings at a regional level (Sena et al., 2013).

In summary, fire's effects on the climate system are diverse in nature and magnitude. The complexity of biomass burning's interactions with the climate system makes this a particularly difficult challenge for scientists who seek to understand the role of fire in climate change or to model future climate behavior. The following section gives an overview of the approaches currently taken by scientists to better understand the roll of biomass burning in global climate.

2.2.2 Biomass burning and greenhouse gas emissions

Emissions from biomass burning can be estimated by modeling and predicting emissions from fire, or through direct observation of gasses near a fire combined with inverse modelling of sources. These are known as the "bottom-up" and "top-down" approaches, respectively (Arellano, 2004). The most common approach to estimating the climate impacts of fire relies on the calculation of emissions from fire using information about fuels and fire characteristics from available datasets. Emissions from fire may be calculated from the following equation (Seiler and Crutzen, 1980):

$$E(X) = \sum_{i=1}^{N} BA_i \cdot BD_i \cdot BE_i \cdot EF_i(X)$$

where N gives the number of vegetation classes assessed and additional parameters are given as:

Burned area (BA) – The land area affected by fire. This measurement is generally derived from satellite data, or in the case of historical reconstructions, projections based on qualitative assessments (Mieville et al., 2010).

Biomass density (BD) – The amount of biomass contained within a given area of land. This is usually parameterized for each vegetation class assessed.

Burning efficiency (BE) – The percentage of biomass within a given unit of area that generally burns. Again, this is often parameterized on a per-vegetation class basis.

Emission factor (EF) – The amount of gas X that is released by the burning of a set amount of biomass within a given vegetation class.

This equation is prescribed by the Intergovernmental Panel on Climate Change (IPCC, 2006) for National Greenhouse Gas Inventory calculations, marking it as a key tool in understaning biomass burning's influence on the climate system.

Emissions from biomass burning across various time periods have been calculated recently (Jain, Tao, Yang, and Gillespie, 2006; Jain, 2007; Mieville et al., 2010; Mouillot and Field, 2005; van der Werf et al., 2010). Estimating emissions is a critical step in understanding the implications of biomass burning for climate change. This task is complicated by the need to determine whether the gross emissions and land cover change from fire signify 1) a climate forcing or 2) a flux or aspect of change that is ultimately canceled by other processes (i.e. vegetation regrowth either in the same area or in other areas that compensate for emissions and land cover change). In addition, a number of additional uncertainties exist.

2.2.3 Uncovering uncertainty

An accurate understanding of biomass burning's effect on the climate system relies on well-constrained measurements of the parameters used in calculating emissions from fire. However, large uncertainties in these estimates are evident in the literature. Here, I review several examples of that uncertainty.

Estimating burned area represents one challenge in understanding the role of biomass burning in climate change. Mouillot and Field (2005) used ASTR satellite imagery, government records, and qualitative information such as burn scars in tree rings to reconstruct a history of global fire for the 20th century. They found that, excluding agricultural fires, 608 Mha per year burned at the end of the last century. Because the influence of fire on carbon budgets is determined by trends in fire rather than the bulk amount of fire, they further examined trends in fire over the century. While fire decreased by approximately 80% in boreal and temperate forests in the Northern Hemisphere, a sharp increase in fire in tropical forests was also observed over the study period, signaling the increasing use of fire for deforestation and agricultural production.

These trends generally agree with previous regional studies of fire activity, but the analysis remains a “best guess” due to various sources of uncertainty within the reconstruction. Sources of bias, error, or uncertainty cited by the authors include: 1) the limited availability of historical records in some countries which necessitated the interpolation of available data over data gaps, 2) significant differences between reports from adjacent countries suggesting substantial biases and difference in data collection methods, 3) a decline in data quality for older fire records, 4) variability in the level of detail of fire records, 5) exclusion of agricultural fires from the analysis, and 6) the assumption of fire regime homogeneity within sub-continent regions (Mouillot and Field, 2005).

These uncertainties result in large discrepancies in the estimated burned areas. The analysis from Mouillot and Field underestimates burned area by up to 60% compared to the findings of Barbosa, Stroppiana, Grégoire, and Cardoso Pereira (1999). In addition, remote sensing data can present biases in burned area estimates. When fires occur at a spatial scale below that of available satellite imagery, fires can remain undetected. This problem has been noted particularly in the African context, where 25-90% of fires in some areas may be excluded from detection (Laris, 2005; Roy and Boschetti, 2009).

Similarly, estimates of emissions from fire are difficult to constrain. One of the difficulties in estimating fire emissions lies in the fact that the ratio of smoldering to burning cannot be easily determined based on available observations or models. Emissions factors are quite different for smoldering and burning and the two are not well correlated. Adding to the difficulty, the ratio is controlled by a variety of local factors including temperature, humidity, soil moisture, and fuel density

(Bond and van Wilgen, 1996). These can, in turn, be related to season and time of day to some extent, but including these factors in models is difficult in part because the relationship is regionally specific (Keywood et al., 2013). Thus, the emission factors and burning efficiency tend to be event specific in ways that are difficult to model.

In addition, uncertainty in emissions estimates themselves remain substantial. Studies have found a two-fold difference between CO emissions estimated by L3JRC, MODIS fire counts, and the Global Burned Area 2000, indicating a high degree of uncertainty currently present within these datasets (Arellano, 2004; Langmann, Duncan, Textor, Trentmann, and van der Werf, 2009; Monks et al., 2009). A 3.4 fold discrepancy between aerosol emissions estimates from two different estimation approaches has also been reported (Kaiser et al., 2012). These results reveal the uncertainty in current attempts to estimate emissions from fire

The final goal of estimating emissions from fire is the quantification of climate forcings due to biomass burning. Bowman et al. (2009) provide a preliminary estimate of climate forcings because of biomass burning, but rely on substantial assumptions about the system. They suggest that only fire which contributes to deforestation influences the climate system, and that that effect is due only to CO_2 released.

In contrast, Sena et al. (2013) studied the direct radiative effects of biomass burning over the Amazon due to aerosols and albedo changes. They found that the radiative effect of albedo was almost an order of magnitude greater than that of the effect of aerosols. A value of -7.3 ± 0.9 W/m^2 for mean annual albedo-change radiative forcing due to fire was reported, versus a value of -0.9 ± 0.3 W/m^2 for aerosol effects. The findings suggest that the gaseous emissions may not be the most important component of fire associated with climate change, a finding that conflicts with the approach taken by Bowman et al. (2009).

Current knowledge about emissions and climate forcings from biomass burning is sufficient to begin to assess global trends. However, the current level of uncertainty regarding the effects of fire on the climate system suggests that it may not yet be possible to state the climate effects of most fire regimes with certainty.

2.2.4 Future directions

Proponents of the use of fire for climate change mitigation suggest that, if low-intensity prescribed fires can reduce the net emission of carbon over time, this could create a net sink for greenhouse gases. The possibilities for this use, however, are expected to be dependent on the characteristics of the specific ecosystem to which it is applied, and preliminary study has not provided evidence that this approach might be effective (Bradstock et al., 2012; Wiedinmyer and Hurteau, 2010). This fact has not stopped climate scientists and policy makers from prescribing specific fire management actions to address climate change, however. The following section addresses these recommendations within the context of current climate science and historical attitudes toward fire.

2.3 Burn Center Narrative

2.3.1 Introduction

Africa is a red continent – a continent on fire. This is the image presented in popular media and scientific literature when addressing the topic of biomass burning. A particularly common theme in the remote sensing and atmospheric science literature holds that Africa is the site of more fires and a greater amount of greenhouse gas emissions from biomass burning than any other continent on the planet. A frequent corollary is that fire in Africa should be limited due to concerns over the effect of fire on vegetation, air quality, and climate change. The literature that perpetuates this "burn center narrative" (Koné, 2012) represents fire in Africa as homogenous and uniformly negative savanna management technique. However, researchers in political ecology and other fields have argued that these depictions rest on largely unquestioned assumptions about burning and its environmental effects.

Specifically, political ecologists claim that previous research has exaggerated the intensity of fires and the homogeneity of landscapes affected by fire (Koné, 2012). In addition, such representations of fire ignore the social and ecological contexts in which fires are set and burn. Understanding the form and content of the burn center narrative, as well as the factors that perpetuate it, can provide insight into climate change and environmental governance. Deconstructing this narrative can point toward a more complete picture of the nuanced role of fire in African landscapes.

This section seeks to describe the constituent assertions and assumptions of the burn center narrative and to explore alternative perspectives. Building on the work of Koné (2012), I argue that the narrative is constituted by four distinct but interrelated characteristics. The narrative 1) identifies Africa as the primary locus of fire and emissions from biomass burning globally, 2) assumes African savanna fire is intense and homogeneous across broad scales, 3) links African fire with the emission of climatically relevant emissions of greenhouse gasses and particulates, and 4) prescribes a reduction in fire frequency and intensity. Drawing from the field of political ecology as well as recent findings in remote sensing and atmospheric science, I explore the nature of the burn center narrative and its implications for savanna management in Africa. Emerging evidence suggests that the narrative is flawed because of inaccurate modeling assumptions and a simplistic representation of African savannas. Some researchers have identified the need to reduce biomass burning within African savannas, a conclusion that others contend is premature. This is particularly true because such recommendations rarely account for the complex relationship between fire and the socio-ecological system in which it occurs. In this section, I argue that fire is one component of the complex socionatural savanna systems of Africa.

2.3.2 Anatomy of the Burn Center Narrative: Linking African fire with global emissions

Extensive research has been conducted on the impact of biomass burning on carbon fluxes, atmospheric chemistry, and radiative forcing (Crutzen & Andreae, 1990). This literature finds that biomass burning impacts atmospheric chemistry in a number of significant ways as the result of emissions from these fires. For instance, CO_2 from anthropogenic biomass burning may contribute as much as 60% of the warming effect caused by CO_2 released from fossil fuel use (Crutzen and Andreae, 1990). Climate science studies have also sought to enumerate the specific contribution of different types of biomass fires across the globe to emissions budgets and climate change (van der Werf et al., 2010; van der Werf, Randerson, Collatz, and Giglio, 2003). This work seeks to attribute emissions to particular fire activities and locations and to quantify the net radiative forcing associated with the emissions. This line of study also investigates methods for mitigation of climate change through human modification of fire regimes. Together, these studies portray fire in Africa as a threat to the planet's climate system, constituting the burn center narrative. Here, I discuss four common elements of the burn center narrative.

2.3.3 Africa as the Burn Center

Africa is consistently identified as the continent that is home to the greatest proportion of all terrestrial fires, with savanna fires making up the majority of all fires on the continent (Barbosa et al., 1999; Crutzen and Andreae, 1990; Delmas et al., 1991; Levine, Bobbe, Ray, Witt, and Singh, 1999; Levine et al., 1995; Mouillot and Field, 2005; Roberts, Wooster, and Lagoudakis, 2009). In particular, the expanding use of remote sensing to detect terrestrial fire has provided convincing evidence that the majority of fire occurs in Africa. This fact is the basis of the depiction of Africa as the "burn center" of the world in more popular mediums of information dissemination (Julia Cole and NASA, 2001; Stanford University, 2004). The portrayal of Africa as the center of global fire activity marks the first element of the burn center narrative. However, the specific nature and effects of this fire is of critical concern to climate change research as well. As I show next, three additional lines of argumentation regarding the nature of fire in Africa contribute to the burn center narrative.

2.3.4 African savanna fire as intense and homogeneous

The nature of fire depends directly on the fuel, climatic, and terrain conditions in which it occurs (Bond and van Wilgen, 1996). To understand the characteristics and history of fire in terms of location, timing, efficiency, emissions factors, and fuel load, one needs to draw on evidence from remote sensing imagery, atmospheric chemistry, and field investigations. Koné (2012) provides a detailed summary of the representation of the characteristics of African fire. He finds that the descriptions of fire in savanna systems within the remote sensing and climate science literature portray this fire as intense and homogeneous. This portrayal results from several factors.

First, Koné notes that the dominant works on global emissions (see review paper by Koppmann, von Czapiewski, and Reid, 2005) rely on a single study of emission efficiency for West African savannas. This study, known as FOS/DECAFE, was performed at a southern, relatively humid savanna study site in Côte d’Ivoire under conditions which, Koné argues, do not reflect the diverse range of fires that occur across the region (Bonsang and Boissard, 1995; Lacaux, Brustet, and Delmas, 1995). The timing of the experiment (between 11-12AM in mid-January), the extent of the fires (100x100m and 10x10km), and the nature of the fire itself (“intensive” or “vigorous” and only occurring in one particular research site) presents a biased image of West African fire. Although other estimates of burning efficiency from Central and Southern Africa exist (Delmas et al., 1999), the application of the parameter estimates obtained from elsewhere on the continent to West African fires is not appropriate or practiced. Current estimates of the impact of fire, then, rely on a single experiment that does not reflect the diversity of the West African savanna systems and is derived from only two particularly intense fires.

Another potential underlying factor in the characterization of African fire as intense and homogeneous lies in the detection of fire itself. Laris (2005) demonstrated that the 1 km resolution MODIS fire product commonly used to characterize global fire failed to detect 80% of burned areas in his study system. Because MODIS imagery has a relatively large lower bound for the detection of active fire ($100m^2$), the type of fire detected is significantly skewed toward large, intense fires (Giglio, Descloitres, Justice, and Kaufman, 2003). This bias is particularly strong in grasslands, where even large active fires are missed by MODIS (Schroeder et al., 2008).

In summary, the burn center narrative presents a view of West African fires that is biased by the nature of the remote sensing and emissions data used. The resulting depiction of fire focuses on fires that are large and intense, obscuring the highly variable nature of fire in savanna mosaics. Although authors do acknowledge these limitations, the conclusions they reach are predicated on such an understanding of fire nonetheless.

2.3.5 Linking biomass burning and global greenhouse gas emissions

A key link in the burn center narrative is the connection drawn between biomass burning and emissions of greenhouse gases. Indeed, the impact of fire on atmospheric chemistry is one of the key research interests driving research on African fire. Therefore, the link between burning and greenhouse gas emissions is critical to understanding the chain of logic of the burn center narrative, which links African fire with climate change.

It is well known that biomass burning can make a significant contribution to global atmospheric chemistry (Crutzen, Heidt, & Krasnec, 1979). Possible effects result from the release of climatically relevant gases and particulates. Each species released has a unique influence on global radiative forcing, and disentangling these effects is a significant challenge. Recently, van der Werf et al. (2010) utilized MODIS fire data to assess the contribution of different fire types and regions to global emissions from fire. They report that, globally, 72% of burned area, 52% of carbon emissions, 44% of CO emissions, and 36% of CH_4 emissions from fire can be attributed to Africa. In particular, van der Werf and colleagues report that savanna fires represented the single largest contribution to global carbon budgets from biomass burning. Thus, literature contributing to the burn center narrative ties African fire to impacts on global atmospheric chemistry.

The relationship between fire and emissions is often described as complex and challenging to characterize. The IPCC Guidelines for National Greenhouse Gas Inventories Programme (IPCC, 2006) are indicative. The authors note that the calculation of "CO_2 and non-CO_2 emissions from fire on all managed land" is a top priority within the Agriculture, Forestry and Other Land Use sector. The Guidelines include a chapter dedicated to the estimation of biomass burning on carbon stocks and carbon emissions. IPCC GHG inventory methods do not require the quantification of CO_2 emissions from grassland fires in recognition of the fact that savanna fires rarely have a net impact on carbon budgets. However, non-CO_2 GHGs must be still be reported (Verchot et al., 2006). These methods include the requirement that emissions be assessed on an annual basis to account for yearly fluctuations, the recognition of the limitation of satellite-derived burn products, and the acknowledgement that burn parameters cannot be scaled accurately. In short, the relationship between fire and atmospheric chemistry is recognized as complex, variable, and difficult to measure.

However, some literature treating biomass burning at the global scale takes a much stronger stance on the role of fire in climate change. Levine et al. (1999) argue that anthropogenic fire can have a “negative impact on … our planet’s climate and on human health.” Indeed, biomass burning is considered a “driver for global change” (Levine et al., 1995). In this context, fire is simply identified as a source of greenhouse gasses without interrogating the nature of these emissions or the net budget for species such as carbon.

The influence of biomass burning on climate change remains in dispute, largely due to the uncertainties in estimates of the impacts of trace gasses and particulates on global radiative forcing. The magnitude and sign of these emissions remains uncertain (Ciais et al., 2011), as does the impact on the global climate. However, it is undeniable that African fire releases a great deal of gaseous and particulate emissions each year. The burn center narrative is constituted by literature that focuses on the substantial quantities of these emissions, which are often portrayed as troubling.

2.3.6 Recommendations to limit fire

The fourth key aspect of the burn center narrative is the common recommendation that fire be controlled to reduce its contribution to climate change. Recommendations that fire should be suppressed or limited to seasons in which fire is less intense are particularly common. Anti-burning recommendations appear in the work of the IPCC and supporting academic literature.

Andrasko et al. (1991) were the first to review policy options that could reduce climate change from biomass burning. That work recommends an increase in “grassland management to reduce fire frequency and area.” Fire control recommendations for grassland management persists within the IPCC. A more recent IPCC report suggests mitigation action to reduce “the frequency or extent of fires through more effective fire suppression; reducing the fuel load by vegetation management; and burning at a time of year when less CH4 and N20 are emitted” (IPCC, 2007). In this discursive framework, climate change and ecosystem degradation are represented as the inevitable outcome of biomass burning. By extension, this framing of the “fire problem” suggests that fire should be suppressed to reduce its negative effects.

Similar recommendations appear in other reports related to climate change. In a report prepared for UNEP by Levine et al. (1999) that synthesizes global wildland fires, the authors “highlight global fire issues and identify opportunities to coordinate international wildland fire prevention, suppression and rehabilitation programs.” An FAO report on dryland pastoralism and climate change (Neely et al., 2009) argues that

"Where possible, alternatives to grassland burning should be found. Measures to control burning to reduce both the intensity and frequency of fires should be put in place to limit negative consequences of carbon and other gaseous emissions, and to reduce degradation of soil and vegetation and associated loss of productivity and ecosystem functions."

Similarly, a 2009 report by the NGO TerrAfrica recommends "more effective fire suppression" in African savannas to reduce frequency and extent of fires (Woodfine, 2009). Although some of these sources explicitly state that savanna fires do not make a net contribution to GHG emissions, they nonetheless fall into the final conceit of the burn center narrative: that fire must be limited in order to reduce negative impacts of fire on climate change and the environment. These recommendations are made in spite of, and often juxtaposed to, the acknowledgement that the contribution of biomass burning to climate change is highly uncertain.

The following section explores emerging counternarratives that challenge the presumptions of the burn center narrative, particularly the prescription that a reduction in fire frequency and extent is called for by existing evidence. Beyond challenging the scientific evidence used to reach this conclusion, critiques leveled against the burn center narrative call for an understanding of the narrative as a historically and politically situated orthodoxy. Revealing the constructed nature of the burn center narrative points to possibilities for alternative approaches to fire management in West Africa.

2.3.7 Counternarratives to Africa as the Burn Center

Recent findings, particularly from within the political ecology climate modeling literature, call into question the logic of the burn center narrative. This effort has been led by Koné (2012), who identified and problematizes the burn center narrative based on the modeling parameters used for global estimates and the characterization of African fire generically. Building on these critiques, I draw out several additional challenges to components of the burn center narrative that can be found in the literature. A growing collection of studies suggest that the conclusions of the burn center narrative may be unhelpful as scientists and policy makers seek to understanding the connections between fire, climate, vegetation, and human management in African savannas.

In his work that is critical of the burn center narrative, Koné (2012) suggests that this body of work constitutes the African "burn center narrative," a narrative that presents a flawed representation of fire in Africa:

> …the "burn center" narrative is problematic for several reasons.… First, the "burn center" narrative simplifies the African savanna as an undifferentiated "biomass." … Second, the narrative's emphasis on highly destructive fires ignores the changes that have occurred in burning regimes of the Sudanian savanna.… Third, despite the statements regarding large amounts of greenhouse gas emissions in the burn center narrative, there is a scarcity of data on the quantity and type of greenhouse gasses emitted from the savannas of West Africa.

Thus, Koné questions the modeling assumptions of fire emissions estimates in the case of West Africa. His central argument asserts that the diversity and temporal variability of fire types that occur in African savannas are not well represented by the parameters used in climate models that estimate emissions from fire.

Certain critiques to this effect have been long established within the literature. J. M. Robinson, (1989) provides an excellent overview of the sources of error in global emissions estimates. Her work points to the "exploding uncertainty" in attempts to extrapolate emissions parameters. These issues remain unresolved, particularly the uncertainty surrounding burning efficiency parameters in West Africa. Only a single additional experiment in West African savannas has investigated burning efficiency since Robinson's article was published. As a result, the values and parameters used in estimates of biomass burning’s contribution to atmospheric chemistry remain a source of substantial model uncertainty.

The literature commonly reports large inconsistencies in burned area estimates both between and within studies (Giglio et al., 2010; Menaut, Abbadie, Lavenu, Loudjani, and Podaire, 1991). Mouillot & Field (2005) report that their estimate of burned area in Africa diverges from other studies by as much as 60%. Giglio and colleagues (2010) find "substantial differences in many regions" between their assessment of fire and other fire products. Elsewhere, we learn that “the true scale of burning across Africa is greater than we can easily measure using 1 km resolution satellite sensors” (Lehsten et al., 2009). Because the area burned is an important input into estimation and attribution of emissions from biomass burning, this lack of certainty raises basic questions about the conclusions of the burn center narrative.

Burn parameters such as efficiency and emission factors are also highly variable. For example, the literature reports median biomass combustion ranges that vary by a factor of more than three (Roberts et al., 2009). Delmas et al. (1991) note that the level of uncertainty around burning efficiency is "highly speculative" in this system, and so adopts an estimate of 25% based primarily on precedent. This practice of modeling based on rough estimations of key parameters continues today (van der Werf et al., 2010). In the case of particulate emissions, Reid, Koppmann, Eck, and Eleuterio (2005) find that modeling is uncertain because of the high standard deviation between experiments within a single study, large discrepancies between studies themselves, and sampling methods and biases that do not reflect the nature of most fires. While this wide variability may represent true variation between sites and environmental conditions, it also raises the point that the selection of parameters in estimating the extent and impact of fire greatly influences the outcome of modelling efforts. The literature constituting the burn center narrative has not adequately addressed these concerns.

Beyond known variability in burn parameters, unmeasured biases in the experimental approaches of climate scientists introduce additional uncertainties in attempts to quantify the impacts of biomass burning. For example, the diurnal dynamics of fire are rarely considered within modeling activities, with the result that important trends may be left out (Roberts et al., 2009). In addition, while global modelers acknowledge that emissions factors differ between broad ecosystem types (Liousse et al., 2004), the models produced do not distinguish between the many types of fire that may occur within a given landscape (Bond & van Wilgen, 1996). Studies tend to rely on single parameters for all African savannas (Liousse et al., 2004). In contrast to this practice, (Koné, 2012) found significant variability in burning efficiency between different vegetation types of the Sudanian savanna zone in Côte d'Ivoire. He also found significant seasonal variation within vegetation types during different periods in the dry season. As a result of the use of their variation, the uncertainty estimates for biomass burning emissions probably underestimate the degree of error.

Studies seeking to understand global atmospheric dynamics and the role played by fire in these dynamics are surely justified even in the face of uncertainty. However, these observations call into question the key assertions of the burn center narrative. First, the uncertainty in burned area estimates reduces the certainty about greenhouse gas emissions due to African fires. The uncertainty in burn parameters also problematizes quantitative estimates between biomass burning and atmospheric effects. In addition, the broad variability in burn parameters between and within ecotypes indicate that the representation of fire in Africa as homogeneous and intense is inappropriate. Finally, the policy relevance of these studies is limited due to the high degree of uncertainty in current estimates of the effects of fire on climate. In light of persistent uncertainty and acknowledged bias, it is difficult to imagine that a justification for the outright suppression of fire in African savannas can be found within the burn center narrative.

Despite a dearth of evidence linking biomass burning with climate change, the burn center narrative has been used as a basis for recommendations that fire should be limited within African savannas. Previous work has shown that exogenous conceptions of nature and natural resources have influenced African societies and landscapes since colonial times (Crush, 1995; Leach and Mearns, 1996). Such work documents the ways in which the application of inappropriate environmental orthodoxies have resulted in negative outcomes for all involved (Forsyth, 2001). I argue that the burn center narrative presents a contextually constructed, orthodox perspective on African fire. This perspective has its origins in European attitudes toward fire that were entrenched during the colonial experience. A recognition of the constructed nature of this narrative presents the opportunity for deeper and more socially relevant engagement with the complex interactions of fire in African landscapes. The burn center narrative can be productively understood as a powerful epistemology with the ability to change the characteristics of lives and livelihoods within Côte d'Ivoire and throughout Africa (Castree, 2014). This section seeks to suggest that the burn center narrative has been constructed in ways that "embody beliefs not only about how the world is, but also how it ought to be" (Jasanoff, 2007).

The long history of anti-fire policies established by European colonizers points to the potentially constructed nature of the burn center narrative. Europeans historically portrayed fire use as an irresponsibility practice of local populations (Kull, 2004), and fire exclusion policies are common in African states today. Against this backdrop, it is not surprising that an anti-fire narrative has arisen within the climate change literature, as it has in other literatures where European perspectives dominate. Historically, anti-fire policy was utilized as a tool in the struggle over natural resources between local populations and colonial governments (Kull and Laris, 2009; Kull, 2004). The extent to which anti-fire orthodoxy may continue to play such a roe has not been explored in the climate change context.

I suggest that anti-fire policy recommendations within the climate change literature can be traced to the historical and political context in which the IPCC and climate scientists perform their research. The possible underpinnings of the burn center narrative include: 1) a long history of anti-fire ideals, or "received wisdoms," emanating primarily from European centers (Kull, 2004; Leach and Mearns, 1996), 2) policies and practices for fire repression that have been implemented around the world (Laris and Wardell, 2006), 3) the "linear model of expertise" which is dominant within science generally and climate science in particular (Beck, 2010), and 4) the coproduction of cultural, institutional, and political contexts of climate researchers themselves.

Thus, the burn center narrative can be understood productively as the outcome of the experiences, biases, and material interests of Europeans. This understanding suggests future avenues through which scientific and political representations of fire in Africa can be made more socially and environmentally relevant.

2.3.8 Savanna fire as an element of socionatural systems

In his work on the burn center narrative, Koné (2012) argues that the narrative misses not only important variability in fire, but also key processes that influence fire over time and space. The models produced by climate science and the experimental parameters used in their production do not account for social processes in particular. Indeed, the burn parameters used for West African fire are derived from experiments performed within a nature preserve "nearly deprived of human influence" (Vuattoux et al., 2006). This, despite the fact that the vast majority of fires in West Africa are set by people to achieve specific aims within highly managed landscapes (Levine et al., 1995). Furthermore, recommendations made in the literature often do not acknowledge the ways in which local interests may shape fire regimes. Instead, broad assumptions are used to make recommendations for the reduction of fire irrespective of local circumstances. This section asses the current literature examining the social aspects of African fire. Having applied the constructivist “hatchet” to the burn center narrative in the previous section, I now suggest that fire may more productively be viewed as a single component of a larger socionatural system rather than as an isolated phenomenon. Actionable conclusions may yet be drawn from global studies of fire.

Evidence suggests that fire acts as an integral component in many socionatural savanna systems of Africa. Fire has been a component of savanna systems in Africa for far longer than humans have been present, and savanna species are adapted to the reality of fire. Many fire-prone systems rely on fire for their propagation (Bond & van Wilgen, 1996). Today, however, humans are believed to play a significant role in the fire regimes in African ecosystems where humans are present (Archibald, Nickless, Govender, Scholes, & Lehsten, 2010), limiting the influence of other variables such as climate. Laris (2011) points to an emerging understanding of common burning regimes in West African savannas based upon fire use patterns for management of rangeland and fallow fields. In this system, two peaks in fire frequency occur corresponding to the use of fire at distinct times in rangeland and fallows. Similarly, spatial patterns of heterogeneity in savanna ecosystems indicate the role of humans in selecting where burning occurs, and where it does not (Eriksen, 2007). Human livelihood interests influence the spatial and temporal patterns of fire in landscapes that depend upon fire. In this view, human and ecological processes become intimately intertwined.

The simplistic anti-fire received wisdom fueled by the African burn center narrative is likely to be inappropriate for socionatural systems. In similar regions where fire suppression “experiments” have been more successfully implemented, the result has been an increase in particularly intense fires resulting in damage to ecosystems and human interests (Bond & van Wilgen, 1996). Furthermore, efforts to impose environmental orthodoxies formulated in distant regions have a long track record of failure (Fairhead & Leach, 1995). Explicit treatment of socioecological variations in fire across space and time is needed to strengthen existing treatments of West African savanna fires in the climate change and land use literature. The constructivist critique suggests that perhaps the most urgently needed improvement to the understanding of fire in African savannas is local input. Local people have already applied a nuanced fire management system to savannas. A socionatural perspective could lead to a more appropriate set of recommendations and policies for West Africa. For example, what are the implications of the burn center narrative for people living in the fire-prone landscapes of West Africa? The following section interrogates the impact of the burn center narrative on policy and livelihoods in Côte d'Ivoire.

2.3.9 Implications of the burn center narrative for policy and livelihoods

The "institutionalization" of environmental orthodoxies addressing degradation has important material impacts, including the direction of research and aid money (Batterbury, Forsyth, and Thomson, 1997) and the setting of restrictive environmental policy (Fairhead & Leach, 1995; Kull, 2004). Recommendations based on climate change research have resulted in the implementation of anti-fire policies in grasslands in Australia, with implications for livelihoods there (Russell-Smith et al., 2013). The following discussions reveal the actual and potential influences of the burn center narrative on policy and livelihoods in Africa generally and Côte d'Ivoire specifically.

Côte d'Ivoire provides an example of the articulation of the burn center narrative with African policy. The formation in 1984 of the Comité National de Défense des Forêts et de Lutte contre les Feux de Brousse (National Committee for Defense of Forests and the Fight against Bush Fires) strengthened the position of anti-fire received wisdom in the environmental policy of Côte d'Ivoire. The entrenchment of this perspective continues today through official representations of fire as a primarily negative force in the landscape. The launch of the Campagne nationale de Lutte contre les feux de brousse 2012-2013 (the 2012-2013 National Campaign to Fight against Bushfires) provides a prime example of the ongoing production of anti-fire perspectives propelled by global environmental narratives. The theme of this initiative is "Unite for Côte d'Ivoire without bushfire," highlighting the current approach to anti-fire sentiment in the country. At the launch of this initiative, the Minister of Water and Forests called for the end of bushfires because they are destructive and, tellingly, contribute to climate change, making explicit reference to the United Nations as the source of this information (Darret, 2012). Global narratives linking fire and climate change are used as justification for the anti-fire policy.

This argument does not intend to lay blame for the anti-fire perspective within Côte d'Ivoire solely at the feet of the burn center narrative and the associated concerns regarding climate change. Ivoirian actors have differentiated interests in fire management, particularly with respect to the protection of capital assets and territorial control. Indeed, Laris (2011) observed that it is common for rural villagers in Mali, who themselves live within burned landscapes, to complain of "too much fire." Residents of fire-prone landscapes do not have unified understandings of fire or fire regime preferences (Eriksen, 2007). However, insofar as the burn center narrative provides legitimacy for particular perspectives within local contestations of natural resource control, it is relevant to consider the validity of this narrative and its potential impact on policy outcomes.

The example of Côte d'Ivoire illustrates the power embodied in representations of the burn center narrative. This narrative privileges particular viewpoints by granting authority to national decision makers to enact particular policies by reference to global expertise. But who wins and who loses because of this policy? An examination of the importance of fire in livelihoods can indicate how people in Côte d'Ivoire use fire.

In the absence of fire, savannas themselves might cease to exist (Bond & van Wilgen, 1996). The welfare of people living in savanna systems is closely tied to the presence and nature of fire as well. Lavorel, Flannigan, Lambin, and Scholes (2006) provide an extensive list of the ecosystem services upon which fire may have a strong impact, including "carbon sequestration, maintenance of soil fertility, atmospheric quality, and climate regulation… direct products people can obtain from harvesting… the quantity and quality of water available… [and] biodiversity and the services it provides to humans." Fire is also used for agricultural purposes. Lavorel, Flannigan, Lambin, and Scholes (2006) suggest that shifts in fire regimes may have important feedbacks on the adaptability of people living in fire-prone systems. They argue that a clear understanding of the motives and practices of fire ignition is needed before policies prescriptions are made to ensure that the interests of local people are represented.

Interestingly, the primary purpose of burning in some landscapes may be fire prevention (Laris, 2013). By this logic, the setting of early, controlled fires ensures that more intense fires do not damage local assets later in the dry season. Areas where fire suppression has been aggressively implemented, the result had often been increasingly large and intense fires (Bond & van Wilgen, 1996). Ironically, anti-fire policies may therefore fail to prevent fires while simultaneously making people more vulnerable to fire damage to assets and a loss of the other goods provided by fire.

Political ecological research suggests that the burn center narrative and the policies it inspires will produce both winners and losers (Robbins, 2012). More detailed study of the ways in which fire acts as a component of socionatural savanna systems in Africa is needed to determine the impact of the burn center narrative on livelihoods in West Africa. The number of identified uses of fire, however, suggests that the burn center narrative could increase the vulnerability of people living in fire-prone landscapes through the promotion of anti-fire policies. Conversely, there may be some opportunities for indigenous communities to benefit from changes in fire practices if they are able to tap into global carbon offset markets (Russell-Smith et al., 2013).

2.3.10 The future of African fire in a warming world

This review is not intended to portray an understanding of African fire as entirely beyond the purview of those who seek to understanding the roll of land use on climate change. Rather, I suggest that past efforts have suffered from large uncertainties because they do not reflect an appropriate understanding of fire in the savannas of West Africa. An improved understanding that better accounts for the human and event-specific dimension of fire will be important for investigation fire's impact on the Earth system.

Opportunities to reduce the uncertainty currently found in global emissions models exist. Koné's work makes a significant step in this direction. However, constructivist critique of the burn center narrative suggests that what is needed most for determining the future of fire in the African savanna is the empowerment of the people who live there to determine the fire regime utilized in these systems. The view that savanna systems are complex socionatural systems, in which nuanced fire management already occurs, reinforces the need for local input. The following section assesses previous work to study fire regimes and the roles of people in them.

2.4 Analysis of Fire Regimes

The season in which a fire occurs influences a number of important variables, including the efficiency of the burn, the ratio of flaming to smoldering (Korontzi, 2005), and the long-term impacts of fire on vegetation. The differences in impact of fire depending on the season is known to and used by people in West Africa, where distinct signals for early season fires related to pastoralism and late season fires related to crop field preparation can be distinguished (Laris, 2011). Understanding the season in which fires occur is relevant for a number of areas of study related to land management and climate change.

The simplest approach to measuring the season in which fire occurs is to divide the burn season year into segments related to the ecological patterns or effects of fires in those segments (Carmona-Moreno et al., 2005). In Côte d'Ivoire, the fire season has been divided into early (Nov-Dec), mid (Jan-Feb), and late (March-Apr) dry seasons (Koné, 2012). Koné showed that, in the Sudanian savanna zone, the season of burning has significant impact on emissions of greenhouse gasses. By enumerating the number or extent of burns in each season, a general summary of fire seasonality may be obtained.

In addition, it is often desirable to create statistics that summarize the characteristics of a particular burn regime. The time of peak burn, the beginning and end of the burn season, and the duration of the burn season are often computed. Several methods for a measure of central tendency of fire have been implemented. Giglio, Csiszar, and Justice (2006) define the peak burn month as the month with the greatest number of fires recorded. Dwyer, Pinnock, Gregoire, and Pereira (2000) define the burn peak as the time point at which 50% of all fires in a burn season have been observed. Zhang, Kondragunta, and Roy (2014) implement a 60-day moving window measure of fire activity and define the point of peak burning as the center of the moving window with the greatest biomass consumption. Finally, Le Page and colleagues (2010) use TIMESAT software to fit a smoothed curve to their burn data and define the peak as the midpoint between the two points of the curve at which 80% of maximum amplitude is reached. No direct comparison of these approaches has been undertaken.

The beginning and end of the burn season has also been measured in several ways. Le Page and colleagues (2010) define these points as the points at which the TIMESAT fitted function reaches 10% of amplitude. Zhang, Kondragunta, and Roy (2014) fit a sigmoid curve to the cumulative fuel consumption data and define the beginning and end of the burn season as the points where 10% and 90% of fuel has been confirmed. Giglio, Csiszar, and Justice (2006) define the length of the burn season as the number of months in which at least 10% of annual fires are observed.

The regularity with which fire returns to an area, or the fire regularity, is also of interest to studies of fire regimes (Laris, Caillault, Dadashi, and Jo, 2015). Measurements of this property across landscapes are limited in the literature, although it has been assessed using the 12-month autocorrelation of burned area times in one study (Giglio et al., 2006).

A major debate in the literature regarding fire regimes in Africa addresses the extent to which they are under human or climatic control (Andela and van der Werf, 2014; Archibald, Nickless, Govender, Scholes, and Lehsten, 2010; Archibald, Roy, van Wilgen, and Scholes, 2009; Grégoire and Simonetti, 2010; Laris et al., 2015). The tension lies between broad patterns in fire prevalence that appear to reflect climatic gradients and the knowledge that people use fire deliberately and variably to achieve certain ends. To disentangle these effects, researchers have utilized field studies, historical records, and remotely sensed data to examine the influence of human and climate variables on fire's characteristics.

An analysis of fire regimes in southern Africa using field and remote sensing data showed that the relationship between fire and climate is significant in protected areas where human impact is limited (Archibald, Nickless, et al., 2010). However, outside of protected areas, this relationship was substantially diminished, an effect the authors attribute to the role played by humans in fire management. Similarly, Andela et. al (2014) use MODIS burned area data in a linear regression model to show that fire has diminished across Africa in association with of intensifying crop cultivation. Similar findings are also reported at smaller scales (Devineau, Fournier, and Nignan, 2010). Despite these findings, climate remains one of the best model predictors of fire activity (Archibald et al., 2009).

Interpretation of these results is complicated by the fact that the studies examine fire regimes using different metrics (i.e. burned area vs. active fire) and examine the impacts on varying measures of seasonality. Discrepancies between studies may be due to these factors. Thus, an examination of the relationship of human and climatic variables to several aspects of the fire regime can help to clarify these effects. In addition, this approach can lend insight into the specific mechanisms by which humans influence fire regimes. The following chapter presents the methods I use to investigate these relationships.

2.5 Tables

Table 1. Defining a fire regime.

Fire characteristic	**Definition**
Intensity	The amount of energy released by a given unit of fire.
Severity	The level of impact of the fire on the ecosystem (i.e. rate of tree death or percent aboveground biomass consumed).
Frequency	The frequency, usually in years, with which fire affects a given area of land, or the time required to burn a specified area.
Seasonality	The annual cycle of fire prevalence on a landscape. The seasonality of fire can be described by the time of peak fire activity, the length of the fire season, or the start and end time of fire activity within the year.
Fuel consumption and fire spread	The amount and type of fuel consumed over a given area. Based upon its vertical location, fire spread can be divided into crown fires, surface fires, and ground fires.

Chapter 3. Methods

3.1 Overview

To address the impact of humans and climate on the fire regime of Côte d'Ivoire, I quantified fire regimes using historical remote sensing data and combined these with available gridded data on climate and anthropogenic factors in a randomForest modelling framework.

3.2 Study Area

Côte d'Ivoire occupies 515 km of coastline on the Gulf of Guinea in West Africa. With an area of approximately 320,000 km^2, the climate of Côte d'Ivoire is dominated by a north-south rainfall gradient controlled by the displacement of the Intertropical Convergence Zone (ITCZ) (Delmas et al., 1999; Koffi, Grgoire, and Mah, 1995). Along the southern coast, the climate is tropical, while the far north of the country is Sudanian. Climate reanalysis data shows that annual rainfall for individual years at locations across Côte d'Ivoire has ranged from under 250 to over 2000mm between 1984-2014 (Fig. 1) and mean temperature has ranged from 23°C to 28°C (Fig. 2). The long-term mean rainfall varies in the northern savannas from approximately 1000mm to over 1400mm (Bassett and Turner, 2006). Inter-annual variation in these climate patterns has been attributed to the El Niño Southern Oscillation and Atlantic sea-surface temperatures in the Sahel of West Africa (Dai, Trenberth, and Qian, 2004; Dai, 2011), although inter-decadal patterns are known to be affected by an array of factors (Rodríguez-Fonseca et al., 2011).

Vegetation cover in Côte d'Ivoire generally mirrors the climatic gradient, with evergreen and tropical forests covering much of the southern half of the country and savannas dominating the north. The northern savannas are differentiated into the Guinean and Sudanian savannas (Vuattoux et al., 2006), and some identify a third sub-Sudanian savanna in the far north of the country (Koné, 2012).

Although the proportion of trees to grasses and the dominant tree species defines the difference between these zones, satellite descriptions of woody vegetation cover show heterogeneous patterns of tree and shrub prevalence within and among these ecotypes (Fig. 3).

3.3 Definitions

I defined the following terms used to describe fire activity. The *fire year* is the 180th day of the calendar year through the 179th day of the following year. This definition was selected because the number of fires in Côte d'Ivoire is generally minimal during the period June to approximately October, and the fire peak tends to occur between December and January. Defining the fire year in this way ensured that the fires occurring within one seasonal cycle from minimal fire to maximum fire and back to minimal fire are assessed as a unit. The *fire density* is the mean number of fires occurring per observation (Giglio et al., 2006; Grégoire and Simonetti, 2010). I defined the *fire peak* as the day of the fire year on which 50% of all fires detected in that year have occurred. Finally, across broader time scales, I identified *fire regularity* as the tendency of fire to occur every year and at the same time each year at a given location.

3.4 Geospatial datasets

In this study, I used a historical archive of multispectral remote sensing imagery to detect the presence of actively burning fire across Côte d'Ivoire, which were then summarized into fire density, fire peak, and fire regularity. Fire statistics were computed for each cell in a 20x20km grid created to cover the area of Côte d'Ivoire. This grid cell size was selected to balance the ability to resolve spatial heterogeneity with the presence of a reasonable number of active fire counts per observation. As predictor variables for random forest regression models, I used existing datasets representing climate, land use, population density, and livestock density (Table 2). All datasets were resampled using bilinear interpolation to fit the data to the same 20x20km grid used to aggregate active fire counts. Data for fire characteristics and environmental variables were merged based on grid cell, as well as date for the fire count and fire peak analyses. Correlation coefficients were calculated between each of the predictor variables (Table 3).

3.4.1 Remote sensing imagery

For this study, I used satellite imagery from the Landsat 4 Thematic Mapper (TM), Landsat 5 TM, and Landsat 7 Enhanced Thematic Mapper Plus (ETM+) sensors. These instruments represent three iterations of the Landsat continuity mission, providing consistent spectral information from 1982 to present at 30m ground sample distance (GSD). Each instrument has a repeat cycle of 16 days, with an 8-day interval between Landsat 5 and 7 during their concurrent operations. The instruments collect blue, green, red, near-infrared, and two shortwave infrared bands. In addition, the sensors detect thermal infrared radiation at either 120-meter spatial resolution in TM imagery or 60m resolution in ETM+ imagery. Each image covers an area of the Earth's surface roughly 180x170 km.

For this study, twenty-one regions, each corresponding to a Landsat Worldwide Reference System (WRS) Path/Row coverage, were selected to cover the land area of Côte d'Ivoire (Fig. 4). All Landsat TM/ETM+ images available for the 21 study regions from the U.S. Geological Survey (USGS) and the European Space Agency (ESA) were obtained for the period 1984-2014 (Fig. 5). In all, 5157 images were obtained. Generally, fewer images were available during the middle of the calendar year, a characteristic of Landsat acquisitions over Africa that has been noted previously (Roy, Ju, Mbow, Frost, and Loveland, 2010). The number of available images per WRS Path/Row ranged from 176 to 275.

I obtained 4468 images from the USGS Earth Resources Observation and Science (EROS) Center. I acquired the images in the Landsat Surface Reflectance Climate Data Record (CDR) surface reflectance processing level. CDR images are derived from Landsat scenes that have undergone radiometric and geometric correction at the 1G, 1Gt, or 1T level. Images are then atmospherically corrected and converted to surface reflectance values using the Landsat Ecosystem Disturbance Adaptive Processing

System (LEDAPS) (Masek et al., 2006). LEDAPS makes use of Second Simulation of a Satellite Signal in the Solar Spectrum (6S) radiative transfer model to adjust pixel values to correct for the effects of water vapor, ozone, geopotential height, aerosol optical thickness, and elevation. In addition, the CDR surface reflectance product includes cloud, cloud shadow, water, and snow identifications determined by the CFmask algorithm (Zhu and Woodcock, 2012).

The availability of Landsat imagery covering Africa in the USGS archive was relatively limited, with a majority of path/rows showing a complete absence between 1989 and 1998 (Roy et al., 2010). To fill these gaps where possible, six hundred eighty-nine radiance images were obtained in terrain-corrected L1G or L1T format from the ESA Earth Online portal. These images were processed using the same procedures applied to USGS Landsat CDR images. First, images were atmospherically corrected and converted to surface reflectance using the LEDAPS processing algorithm, version 1.3.1, and ancillary data available as of 9/15/2014. Cloud, cloud shadow, water, and snow pixels were identified using the CFmask algorithm (Zhu and Woodcock, 2012). Finally, images visually identified as being affected by substantial data loss due to bit-flip errors were removed from the dataset. The distribution of all Landsat images used in time is shown in figure 5.

To facilitate further processing, I used nearest-neighbor interpolation to align and crop all images from the ESA and USGS using a single reference image for each of the 21 study regions.

3.4.2 Active fire detection and fire summaries

I adapted an active fire detection algorithm described in Schroeder et al. (2008). This approach uses emissions caused by small fires in the shortwave infrared (as opposed to thermal IR), and has been found to be useful in detecting fires burning at between 700°C to over 1200°C (Rothery et al., 1988). This approach has been used in a variety of active fire applications, including validation of the widely-used MOD14 MODIS fire product (Schroeder et al., 2008).

The algorithm use two thresholds based on differences and ratios between Landsat's shortwave infrared (band 7) and near infrared (band 4):

$$R_{74} = \frac{\rho_7}{\rho_4} > 2.5$$

$$D_{74} = \rho_7 - \rho_4 > 0.3$$

where R_{74} is a the ratio of the reflectance of Landsat band 7 to band 4 and D_{74} is the difference between Landsat band 7 and band 4. Any pixel in which the given threshold is exceeded was identified as a fire pixel. Unlike Shroeder et al. (2008), I did not include an additional contextual detection step.
All raster calculations were performed using the rasterEngine function from the `spatial.tools` package in R (Greenberg, 2014).

Fire detection pixels from each analyzed image were converted to polygons and merged to a SpatiaLite database. Over 2.7 million raw fire detection polygons were obtained. All polygons covering less than four Landsat pixels (2700 m^2) were removed from the dataset to eliminate spurious detections due to cloud and water masking errors or data corruption. Additionally, all polygons from images that indicated substantial fire detections over large water bodies due to cloud masking errors were eliminated from the dataset. Since active fires from a single ignition source can diverge spatially, I merged any fire polygons found within 500m of each other into a single fire event.

To validate the detection algorithm, I randomly selected an N=400 member subsample of the resulting fire polygons for visual validation. Each detected fire was displayed in spatial and temporal context using Landsat bands 5, 4 and 3 RGB false color images. The detected fires were determined to be true active fires or in error based on the spatial patterns of fire, the presence of smoke, apparent burned areas in subsequent images, and presence of an elevated band 5 reflectance. The rate of commission error was calculated for the fire detections.

3.5 Fire statistics

3.5.1 Fire counts

I calculated the number of fire polygons per time interval for each 20km by 20km cell. I corrected the counts for grid cells in which part of the cell was missing data due to cloud cover, cloud shadows, water, or other missing data errors following Giglio et al. (2006) and Venkataraman et al. (2006):

$$C_{a,i,j} = \frac{C_{raw,i,j} * NP_{all}}{NP_{clear,i,j}}$$

where $C_{a,i,j}$ is the adjusted fire count in cell i at time j, $C_{raw,i,j}$ is the original fire count , NP_{all} is the total number of pixels in each 20km x 20km grid square (444,444 pixels), and $NP_{clear,i,j}$ is the number of clear, unmasked pixels. Fire counts obtained from an image in which less than 5% of a grid cell was visible were removed for that grid cell.

3.5.2 Fire peak day

I calculated the annual fire peak day for each 20km x 20km grid cell from the fire count data, defined as the day of the fire year on which 50% of all fires observed for a grid cell in a year have occurred. Each year was divided into 16-day bins, and the mean number of fires detected for each 20km grid cell, year, and bin was calculated. This corrected for situations in which more than one sensor had data available during a 16-day window, most commonly during the period during which both Landsat 5 TM and Landsat 7 ETM+ were both collecting data. For grid cells with missing data for a given 16-day bin, I performed a linear interpolation of the fire count data from the bracketing time periods. If a grid cell had a continuous period of missing data lasting 64 days or more for a single year, the grid cell's data for that year was removed from the analysis.

3.5.3 Fire regularity

Periodic components of the data were assessed with a Lomb-Scargle periodogram for each grid cell across all uninterpolated fire counts (Scargle, 1982; Thieler, Backes, Fried, and Rhode, 2013). This technique has been used elsewhere to examine the periodicity of fire (Giglio, Randerson, and Van Der Werf, 2013). Importantly, the Lomb-Scargle approach is robust to irregularly sampled data, including periodically sampled data, allowing me to make use of all available fire count data, including from those years for which missing data prevents the calculation of an accurate fire peak. I utilized the `RobPer` package in R (Thieler, Rathjens, & Fried, 2015) to conduct the analysis for all grid cells with 10 or more time periods in which fire was observed.

To investigate the spatial distribution of the strength of annual periodicity, I extracted the strength of the periodicity at 12 months for each grid cell. This value represents the R^2 value of a least-squares regression of the data to sine and cosine functions with frequency equivalent to annual periodicity (Thieler et al., 2013).

3.6 Predictor Variables

3.6.1 Temperature and Precipitation

Air temperature at 2 meters and precipitation grids were obtained from the Modern-Era Retrospective Analysis for Research and Applications (MERRA) reanalysis product (Rienecker et al., 2011). The data are generated using Version 5.2.0 of the Goddard Earth Observing System Model, Version 5 (GEOS-5) Data Assimilation System and are provided at 1/2 x 2/3 degree resolution. This reanalysis was selected due to enhancements in precipitation modeling over other reanalyses such ERA-Interim and the Climate Forecasting System Reanalysis (CFSR). The temperature at the time of the Landsat acquisition was extracted, approximately 10am local time.

For each location and time, I calculated the monthly total precipitation, as well as the mean annual precipitation for over the past two calendar years. I refer to the later value as the two-year antecedent precipitation. For temperature data, I calculated the mean temperature for each year. Only data for days on which Landsat overpass occurred were included in the temperature means. Finally, I calculated the annual mean temperature and precipitation for each grid cell over all years. These values were used is the randomForest models as described below depending on the time-scale of each model.

3.6.2 Palmer Drought Severity Index

Monthly Palmer Drought Severity Index data were obtained from the National Center for Atmospheric Research (NCAR) Climate Analysis Section for global land areas for the period 1984-2012 on a 2.5° grid (Dai et al., 2004; Dai, 2011). The Palmer Drought Severity Index (PDSI) represents the deviation from climatic norms in moisture supply by month (Alley, 1984) and is derived from precipitation, temperature, streamflow, soil moisture, and soil water-holding capacity datasets.

3.6.3 Crop, pasture, and tree cover

Africa subsets of the Global Agricultural Lands in 2000 croplands (Ramankutty, Evan, Monfreda, and Foley, 2010a) and pastures (Ramankutty, Evan, Monfreda, and Foley, 2010b) datasets from the Center for International Earth Science Information Network (CIESIN) were obtained at 5 arc-minute resolution via the NASA Socioeconomic Data and Applications Center (Ramankutty, Evan, Monfreda, and Foley, 2008). These datasets are derived using multiple linear regression to predict percent cropland and pasture from satellite land cover classifications (BU-MODIS and GLC 2000). An agricultural inventory dataset is used to estimate model parameters, and predictions are adjusted to match FAOSTAT administrative unit level statistics for croplands and pastures. From the percent cropland and pasture data, I calculated the proportion of agricultural land in pasture as the percent of agricultural land divided by the sum of pasture and cropland percent covers.

Percent woody cover was estimated using the MODIS Vegetation Continuous Fields (MOD44B) collection 5 woody vegetation layer at 250 m resolution for the year 2000 from the Global Land Cover Facility (DiMiceli et al., 2011). The data relies on a MODIS woody vegetation cover classification machine learning algorithm trained using manually classified Landsat images verified with Ikonos, Quickbird, and other high-resolution imagery (Carroll et al., 2011).

3.6.4 Population Density

The Rural Population Density 2000 dataset was obtained from FAO at 5 arc-minute resolution (Salvatore, Pozzi, Ataman, Huddleston, and Bloise, 2005). The dataset was created using recorded populations for administrative units distributed over a grid based upon transportation networks, urban centers, elevation, and land cover.

3.6.5 Cattle Density

To estimate the effect of grazing on fire regimes, I obtained the Gridded Livestock of the World v. 1 dataset (T. P. Robinson et al., 2014). This dataset is prepared using bootstrapped regression on environmental variables including vegetation, climate, topography, and demography. The results of the regression are adjusted to match FAO livestock density records where available. For Côte d'Ivoire, the dataset reflects cattle density data recorded by the Ministère de l'Agriculture et des Ressources Animales, Direction de la Programmation, Côte d'Ivoire: Recensement National de l'Agriculture in 2001.

3.7 Analysis

I expected the fire regime is to have non-linear relationships with some predictor variables (Archibald et al., 2009) as well as interactions between predictors. Therefore, I selected randomForest (Breiman, 2001) as my regression model that explored the relationships between fire regime and natural and anthropogenic predictors, while accounting for the complexities of the dataset.

I ran three random forests regression models on the active fire data to assess the relationship between human and environmental factors and the fire activity statistics. The models were run using the `randomForest` package in R (Liaw and Wiener, 2002). Within each random forest model, 500 regression trees were run for each forest. The importance (Breiman, 2001) and partial effect (Friedman, 2001) of each predictor variable on the fire response variable was calculated and assessed. For each model, the importance was calculated as the average percent increase in the mean square error of each tree when the variable is randomly permuted. The results of each model were assessed based on total variance explained, the variable importance and the patterns in the partial effect plots.

To identify the primary determinants of fire density within the year and across space and time, I first ran a model relating 155,882 16-day binned fire counts to available predictor variables. Predictor variables included monthly rainfall, daily temperature, monthly PDSI, 2-year antecedent precipitation, population density, percent woody vegetation, percent cropland, percent pasture, cattle density, year, and day of year of observation. This model was run on the fire count data up to 2012 only due to missing PDSI data after 2012.

Next, I constructed a random forest regression model examining the relationship between fire peak and available data. I used 3981 fire peaks calculated each year for each grid cell where sufficient observations were available. This model, which also covered data through but not after 2012, included 2-year antecedent precipitation, annual mean Palmer Drought Severity Index, annual mean temperature, population density, cattle density, percent pasture, percent cropland, percent woody vegetation, proportion of agricultural land as pasture, and year.

Third, a model related the strength of the annual periodicity for the 504 grid cells with sufficient fire data to predictor variables using data over the period 1984 to 2014. Predictor variables used in this model included mean annual rainfall, mean annual temperature, population density, percent woody vegetation, percent cropland, percent pasture, and cattle density.

The results of each model were assessed based on the variable importance and partial effect plots obtained. The relative importance of each predictor in each model was considered. In addition, the trends apparent between each predictor variable and the fire activity response was assessed using the partial effect plots. Together, these indicated the roll played by important predictor variables in the various aspects of fire activity in Côte d'Ivoire.

3.8 Figures and Tables

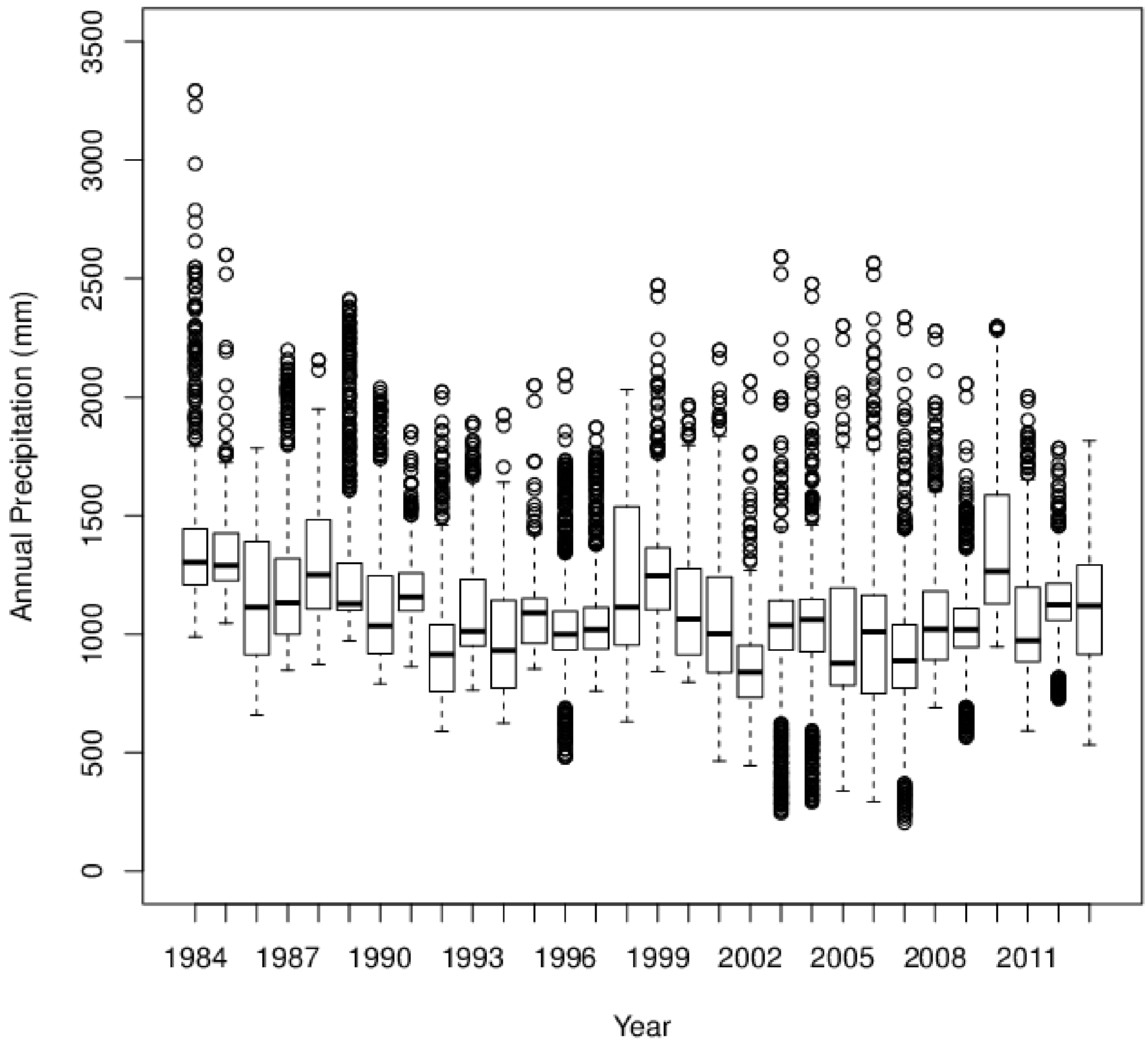

Figure 1. Boxplot of rainfall across Côte d'Ivoire 1983-2014. Each data point represents one 20km by 20km grid location within Côte d'Ivoire. Data is derived from Modern-Era Retrospective Analysis for Research and Applications (MERRA) reanalysis calculated using rain gauge and remote sensing data.

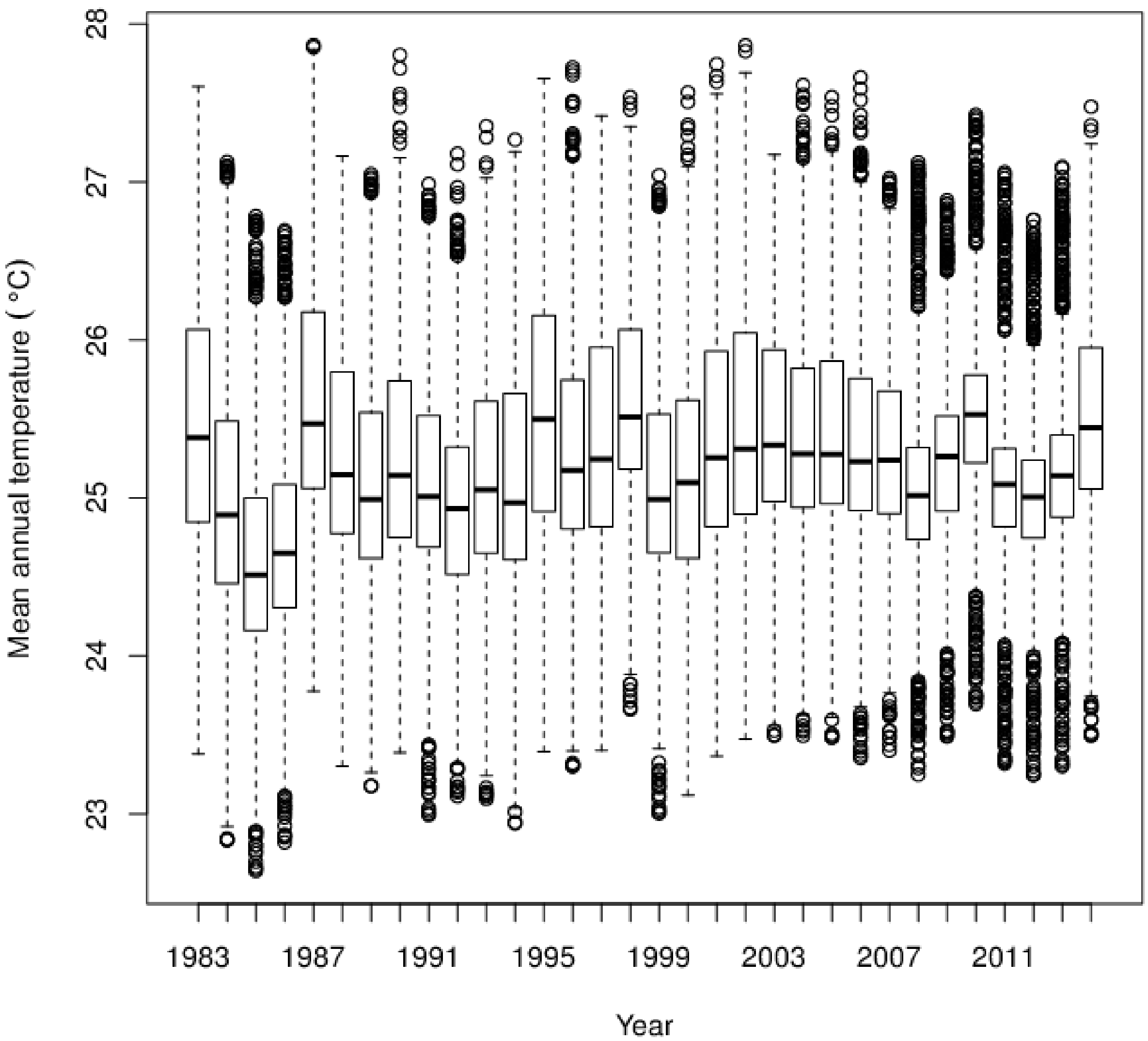

Figure 2. Boxplot of temperature across Côte d'Ivoire 1983-2014. Each data point represents one 20km by 20km grid location within Côte d'Ivoire. Data is derived from the Modern-Era Retrospective Analysis for Research and Applications (MERRA) reanalysis product.

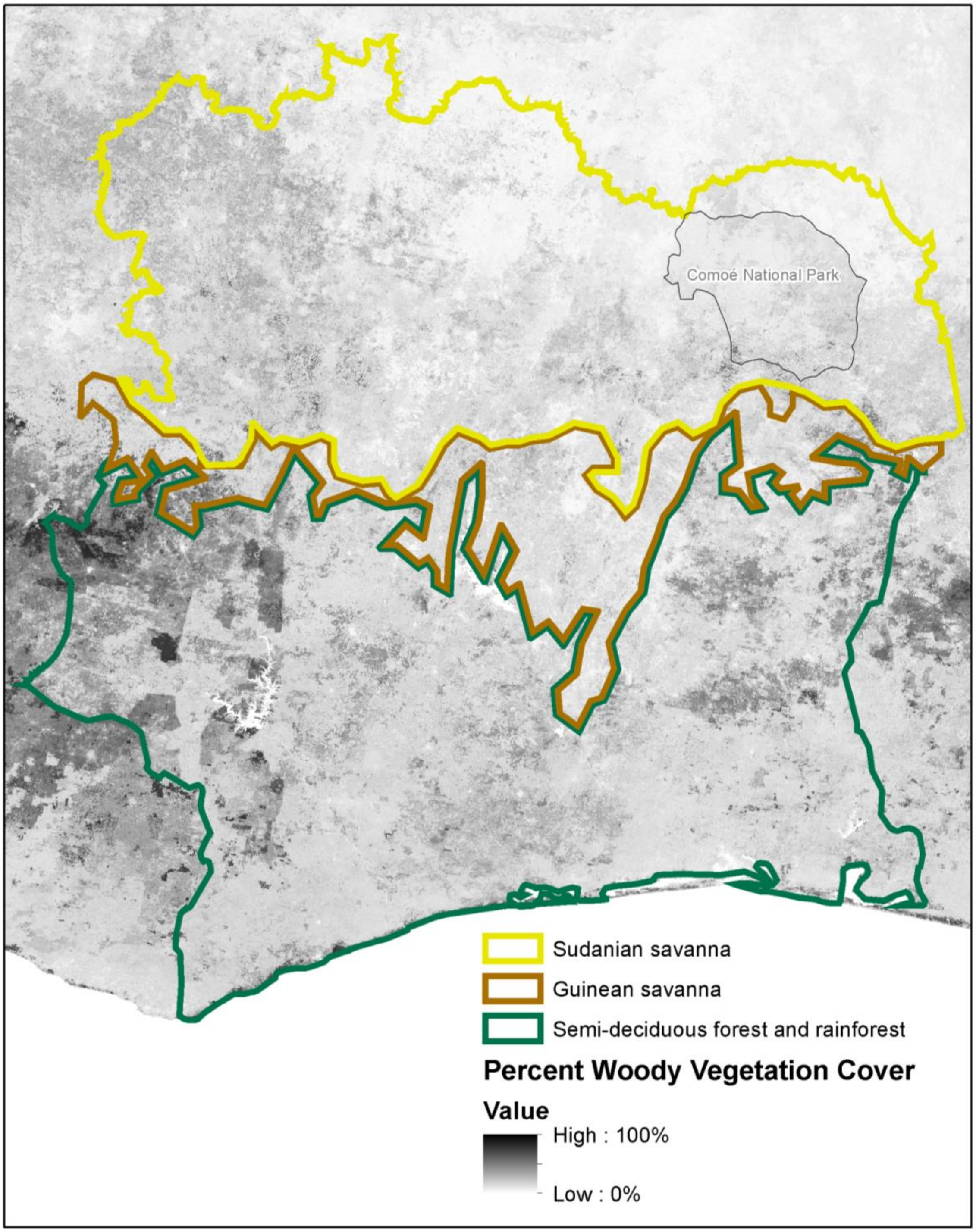

Figure 3. Percent woody vegetation cover in the savanna and woodland regions of Côte d'Ivoire. Woody vegetation data obtained from MODIS Vegetation Continuous Fields (MOD44B). Ecotype boundaries are approximated from Vuattoux et al. (2006).

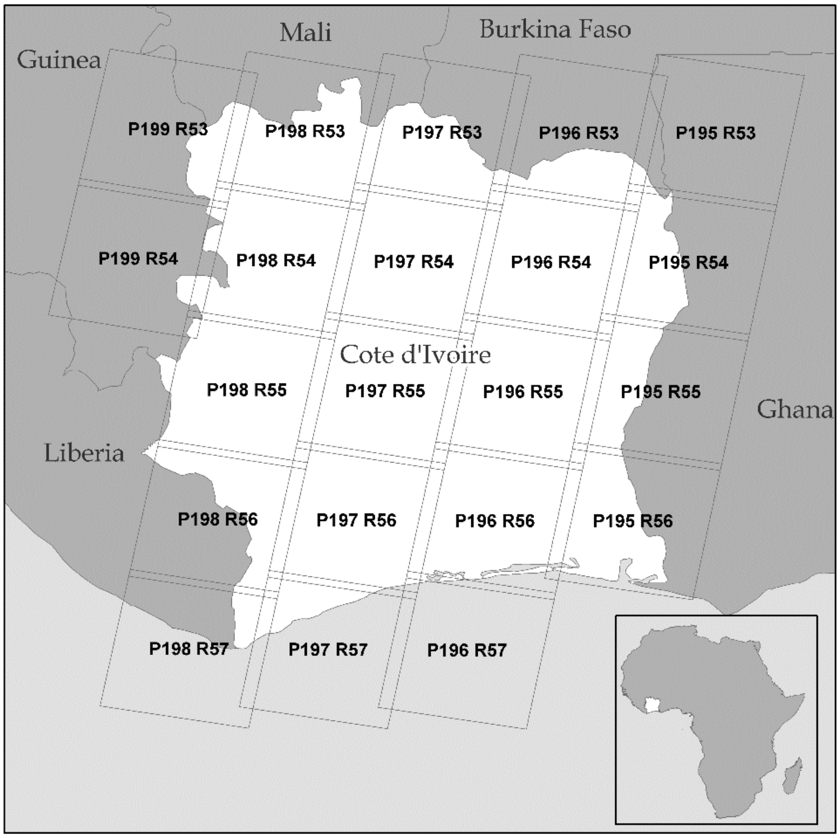

Figure 4. Coverage of Landsat scenes utilized for fire detection as defined by the Landsat Worldwide Reference System.

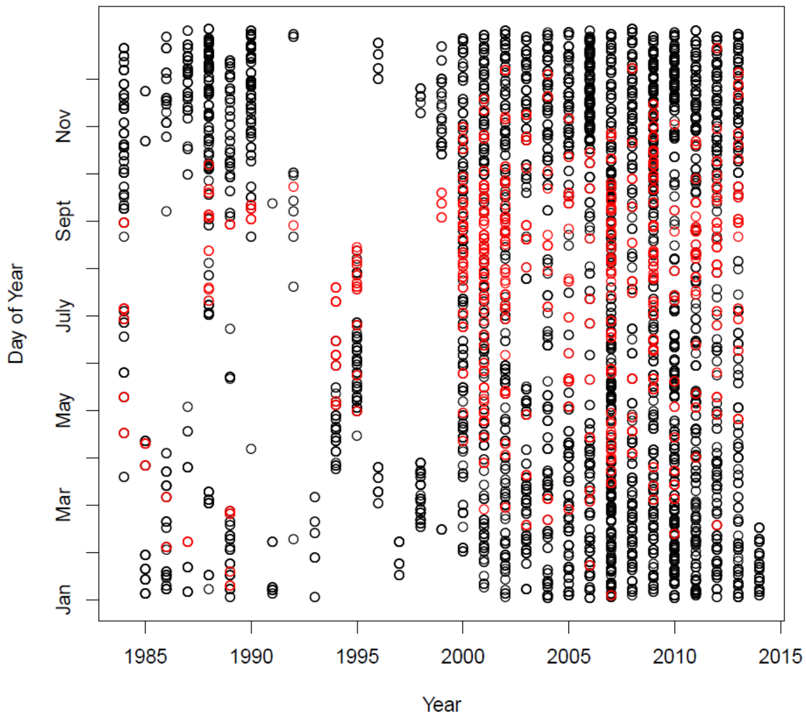

Figure 5. Temporal distribution of Landsat images for Côte d'Ivoire used in this analysis. Points shown in red represent images effected by >90% cloud cover.

Table 2. Predictor datasets.

Variable	Source	Spatial Resolution	Temporal Resolution	Citation
Air temperature at 2 meters (°C)	Modern-Era Retrospective Analysis for Research and Applications (MERRA) reanalysis product, tavg1_2d_slv_Nx dataset	1/2° x 2/3°	Daily	Rienecker et al., 2011
Total precipitation (mm)	Modern-Era Retrospective Analysis for Research and Applications (MERRA) reanalysis product, tavgM_2d_mld_Nx dataset	1/2° x 2/3°	Monthly	Rienecker et al., 2011
Palmer Drought Severity Index (PDSI)	National Center for Atmospheric Research (NCAR) Climate Analysis Section	2.5°	Monthly	Dai et al., 2004; Dai, 2011
Pasture cover (%)	Global Agricultural Lands in 2000	5 arc-minute resolution	Year 2000 data only	Ramankutty, Evan, Monfreda, & Foley, 2010b
Cropland cover (%)	Global Agricultural Lands in 2000	5 arc-minute resolution	Year 2000 data only	Ramankutty, Evan, Monfreda, & Foley, 2010a
Population density (persons per km^2)	FAO Rural Population Density 2000	5 arc-minute resolution	Year 2000 data only	Salvatore, Pozzi, Ataman, Huddleston, & Bloise, 2005
Cattle density (head per km^2)	Gridded Livestock of the World v. 1	3 arc-minute resolution	Year 2005 data only	Robinson et al., 2014
Woody vegetation cover (%)	MODIS Vegetation Continuous Fields (MOD44B)	250 m resolution	Year 2000 data only	DiMiceli et al., 2011

Table 3. Correlation between the independent variables used in this analysis. Variables with multiple values in time are averaged over the study period for all grid cells. PDSI is not shown due to the index's representation of climate anomalies. Correlations greater than 0.5 are noted in bold.

Percent Woody Vegetation							
0.12	Population Density						
-0.19	-0.10	Percent Crop					
-0.41	-0.42	0.32	Percent Pasture				
-0.32	-0.06	-0.10	0.33	Cattle Density			
-0.45	-0.42	0.05	**0.84**	0.48	Pasture: Crop		
0.05	0.12	-0.17	-0.39	-0.14	-0.46	Precipitation	
-0.55	-0.23	-0.03	0.44	**0.51**	**0.51**	0.34	Temperature

Chapter 4. Results

4.1. Active fire validation

I detected 51,364 individual active fires across Côte d'Ivoire in all years of the study. The error of commission rate for the active fire detections was 6.25% (Table 4). Interpolation and bias removal resulted in 100,550 binned fire counts, including zero counts, out of 604,643 possible data bins.

4.2. Fire density results

Across Côte d'Ivoire, fire density shows an increase in the number of fires per observation from south to north (Fig. 6). A substantial degree of heterogeneity along this gradient and within each ecotype is apparent, however. Areas of highest fire activity are interspersed among areas of lower occurrence in the north. An area of especially high fire density is concentrated in the northeastern portion of the country, which includes the large Comoé National Park (Fig. 3). There is also an area of notably high fire activity in the southwest coastal area of Côte d'Ivoire. A lower than average amount of fire is seen in the area surrounding the large city of Korhogo in the center north of the country.

The distribution of fire density within the year provides an indication of the seasonality of fire. A summary of gridded fire counts across the fire year exhibits a strong peak in activity between January and February in both Guinean and Sudanian savannas (Fig. 7). In contrast, little seasonality in fire density can be observed in the southern forests (Fig. 7).

The amount of variability explained by the fire density vs. human and climate factor model was 20.5%. The top five variables, ranked by importance, were all climate or climate-proxy variables: temperature, day of year, 1-month precipitation, year, and PDSI (Fig. 8). Cattle density is the sixth most important variable. The partial dependence model for temperature showed that fire density generally declined with increasing temperatures (Fig. 9). Fire density peaked during the middle of the fire season. Minor peaks in fire activity are also seen in May and early November. Trends in fire density over the years included in the study also show variation, though a clear direction in fire activity is not apparent. 2-year antecedent precipitation showed high fire density at high and low values relative to intermediate rainfall values. A similar pattern appears for PDSI values. In contrast, 1-month antecedent precipitation primarily shows a negative correlation with fire density.

The model shows that increasing cattle density is associated with higher fire densities, a trend that is apparent with increasing pasture cover as well. Intermediate values of population density and percent cropland are associated with the lowest levels of burning.

4.3. Fire peak results

A total of 5482 peaks were calculated across all grid cells in all years, representing approximately 6 years of fire observation per grid cell per year. The number of observations per grid cell ranged from one to 14. The distribution of fire peaks over time is shown in figure 10. Two hundred fifteen grid squares, primarily located in the southern half of the country, had no fire peaks recorded in any year. The timing of peak fire varied between years across the fire peak dataset (Fig. 10), although the data do not indicate a linear trend in the timing of peak burn over the years of this study. However, patterns in interannual variability of the fire peak appear.

The average fire peak within the northern savanna lies mostly between late December and early February, with spatial patterns in timing of peak burn apparent (Fig. 11). Notably, a band of late fire seasonality cuts from north to south through the central northern area around Korhogo. Where fire occurs in the south, the fire peak tends to occur relatively later in the fire year compared to fires in the north.

The peak fire day of year model had the lowest predictive power of the three models, with 15.2% of the variance explained in the model (Fig. 8). However, a number of variables show important trends. Climate plays the largest role, with peak burn occurring later in the year with increasing temperature, precipitation, and high levels of drought (Fig. 12). Woody vegetation is associated with later fire activity, while areas with high cattle density and percent pasture cover show earlier fires. The model shows more complex patterns associated with population and percent cropland.

4.4. Fire regularity

Overall, annual periodicity dominates the fire periodogram for the country as a whole, with characteristic harmonic peaks at higher frequencies (Archibald et al., 2009) (Fig. 13). Plotting the strength of the annual signal of fire at available locations within Côte d'Ivoire reveals that the greatest regularity of fire is concentrated in the north and west of the country (Fig. 14). In contrast, areas in the southeastern portion of the savanna zones showed relatively low fire regularity. Few southern areas had a sufficient number of fire observations to calculate a meaningful level of annual regularity.

The fire regularity randomForest model showed highest explanatory power of the three models, with 52.1% of the variance explained. Mean temperature was the best predictor of fire regularity, with increasing regularity in locations with higher temperatures (Fig. 15). Mean precipitation had the opposite effect, with increasing rainfall leading to greater irregularity in the fire regime. Several indicators of land use showed clear relationships with fire regularity as well. Increasing population is associated with lower fire regularity, while higher fire regularity is found where there is a greater density of cattle and a higher proportion of pasture cover.

A comparison of the patterns of fire density, peak, and regularity exposes the interrelationship, or lack thereof, of these fire characteristics. In the east, areas of high fire density show relatively low regularity. Yet areas of high density in the northwest show high regularity as well. Similarly, a strong contrast between December and January fire peaks is apparent in the central north, but both areas show high regularity of fire. Finally, fire peak and density appear to be nearly independent in the savanna region.

4.5. Figures and Tables

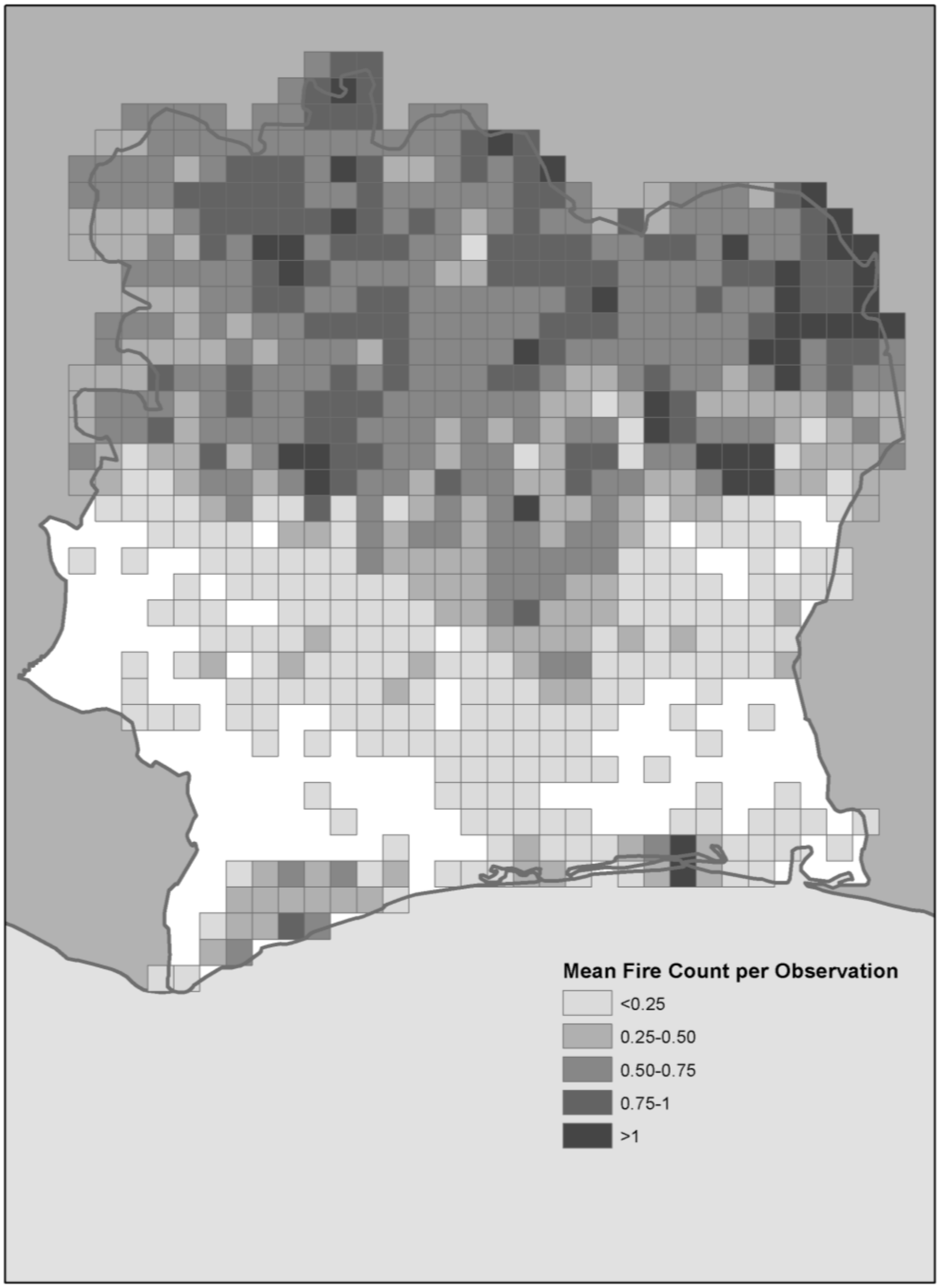

Figure 6. Spatial distribution of mean fire density per observation calculated by averaging available data over all years in each grid cell.

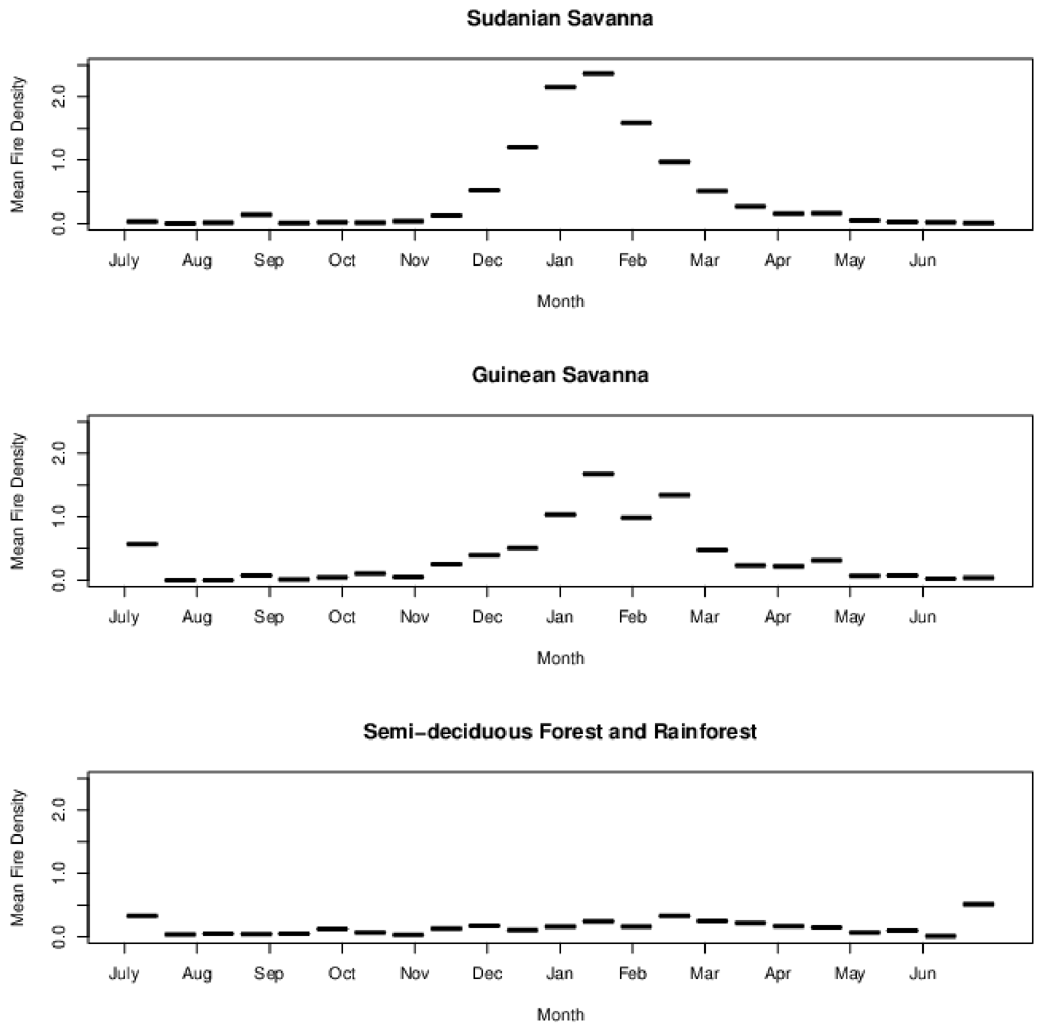

Figure 7. Mean density of fire across each ecotype in Côte d'Ivoire as defined by Vuattoux et al. (2006).Data for all years and all locations are averaged over 16-day intervals. Each interval is represented as a horizontal bar spanning the interval represented.

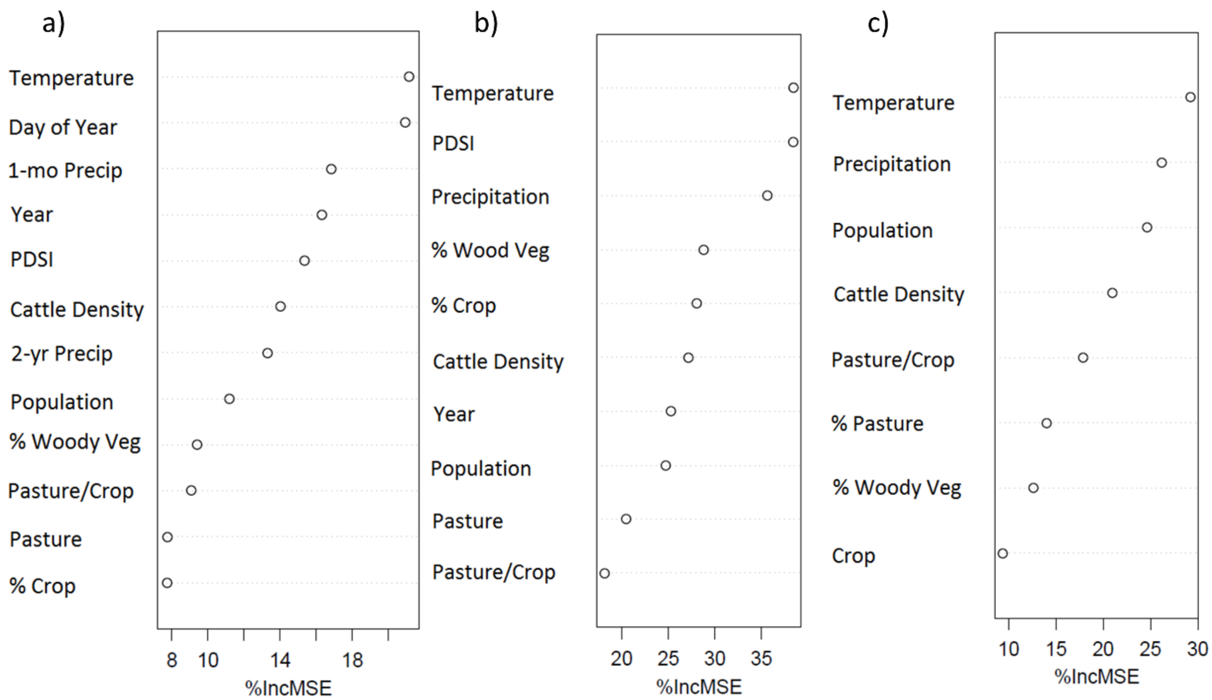

Figure 8. Variable importance ranked from greatest to least importance for a) fire density, b) fire peak day of year, and c) fire regularity. The percent increase in mean square error (%IncMSE) represents an increase in mean square error for the model prediction resulting from random permutation of the given variable.

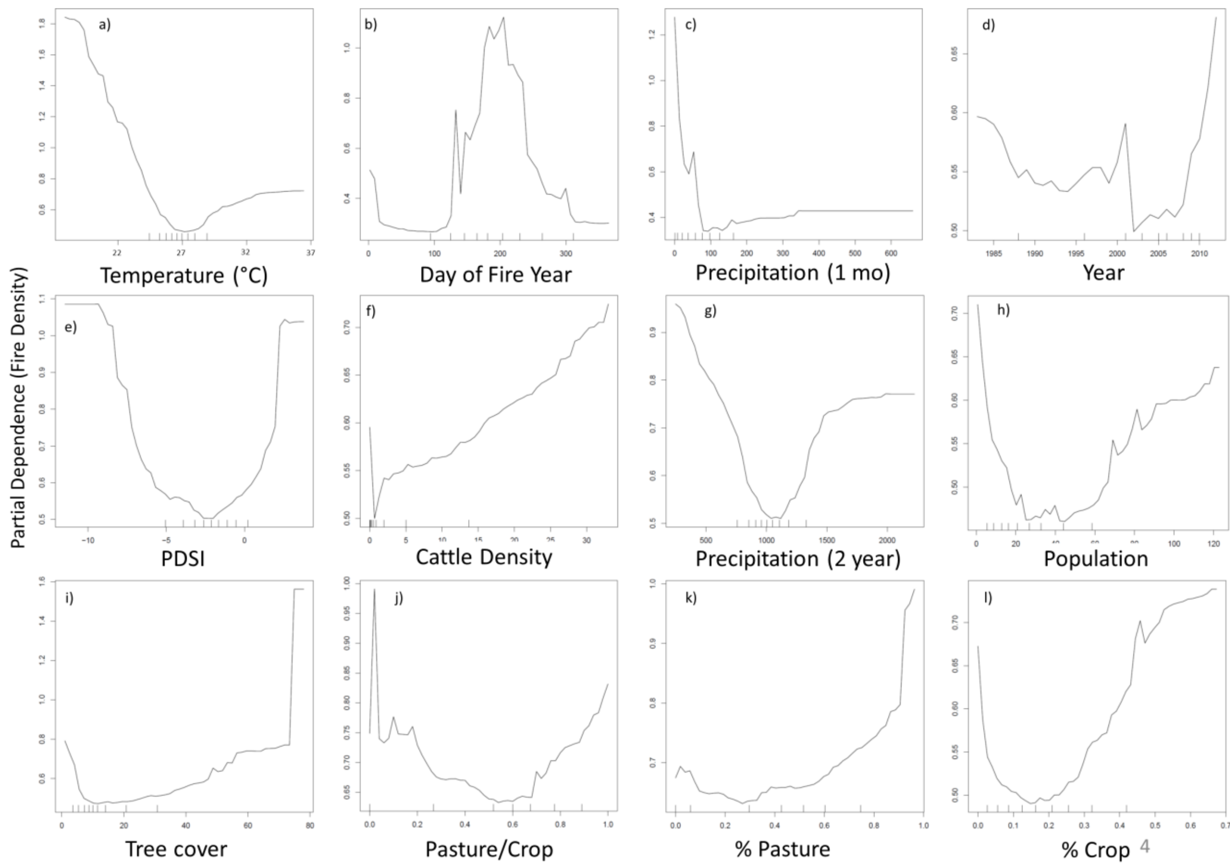

Figure 9. Partial dependence of fire density on independent variables as estimated by a random forest model. Plots show, in order of decreasing importance, the marginal effect on the predicted day of year attributed to a) temperature, b) day of year, c) 1-month antecedent precipitation, d) year, e) PDSI, f) cattle density, g) 2-year antecedent precipitation, h) population density, i) % woody vegetation cover, j) proportion of agricultural land in pasture, k) % pasture, and l) % cropland.

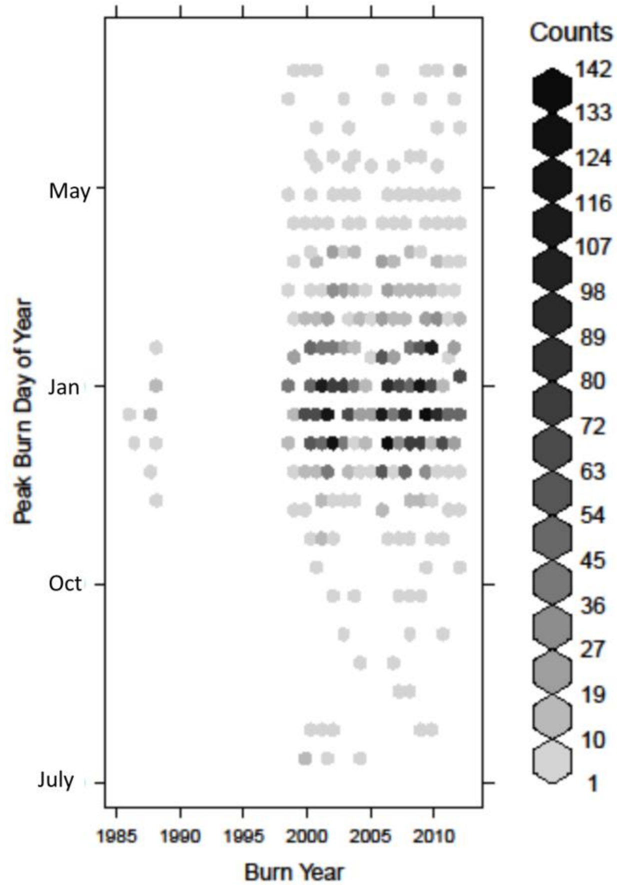

Figure 10. Density of fire peaks within the year and across all years for Côte d'Ivoire. Counts represent the number of grid cells with a fire peak within the day range shown on the y-axis. The majority of observations prior to 1999 are removed from the dataset due to more than 4 consecutive points of missing data during the fire season.

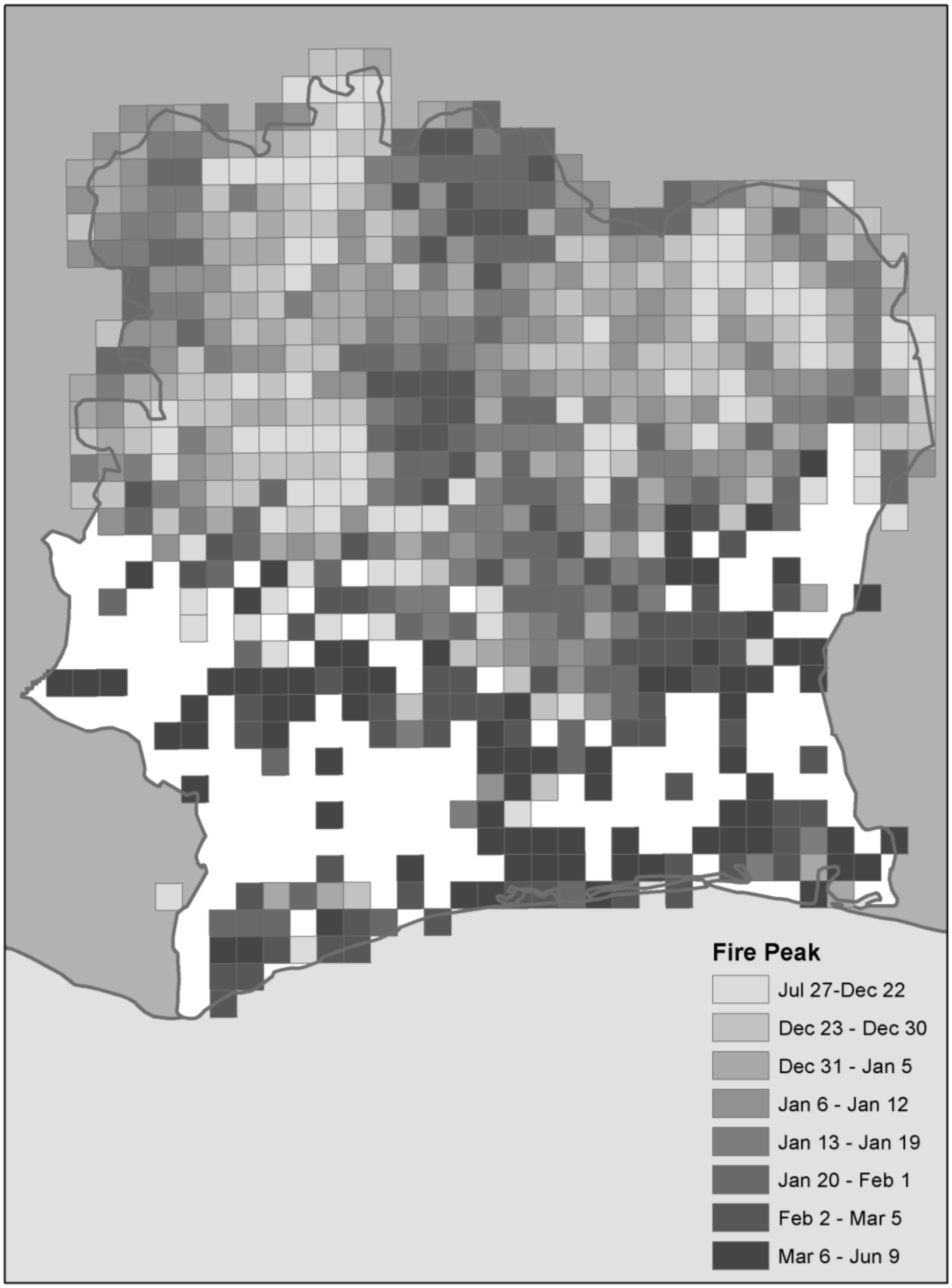

Figure 11. Spatial distribution of mean fire peak calculated by averaging available data over all years in each grid cell.

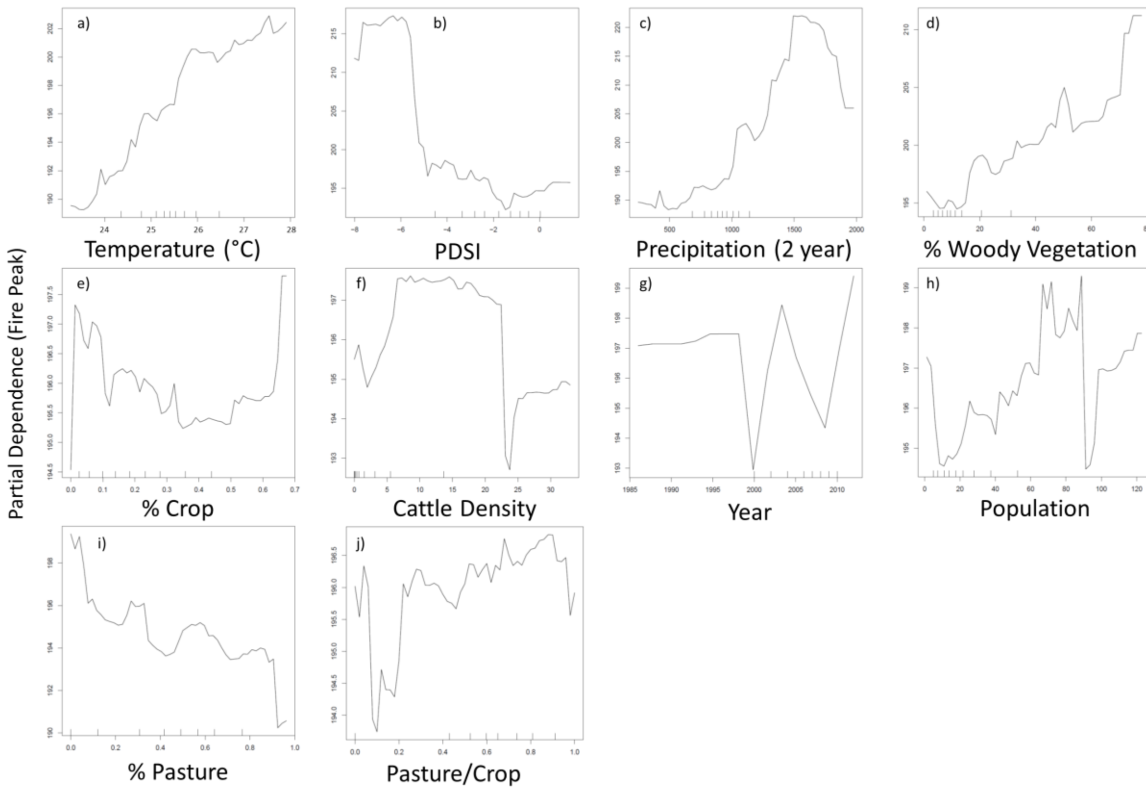

Figure 12. Partial dependence of fire peak day of year on independent variables as estimated by a random forest model. Plots show, in order of decreasing importance, the marginal effect on the predicted day of year attributed to a) temperature, b) PDSI, c) precipitation, d) % woody vegetation, e) % cropland, f) cattle density, g) year, h) population density, i) % pasture cover, and j) proportion of agricultural land in pasture.

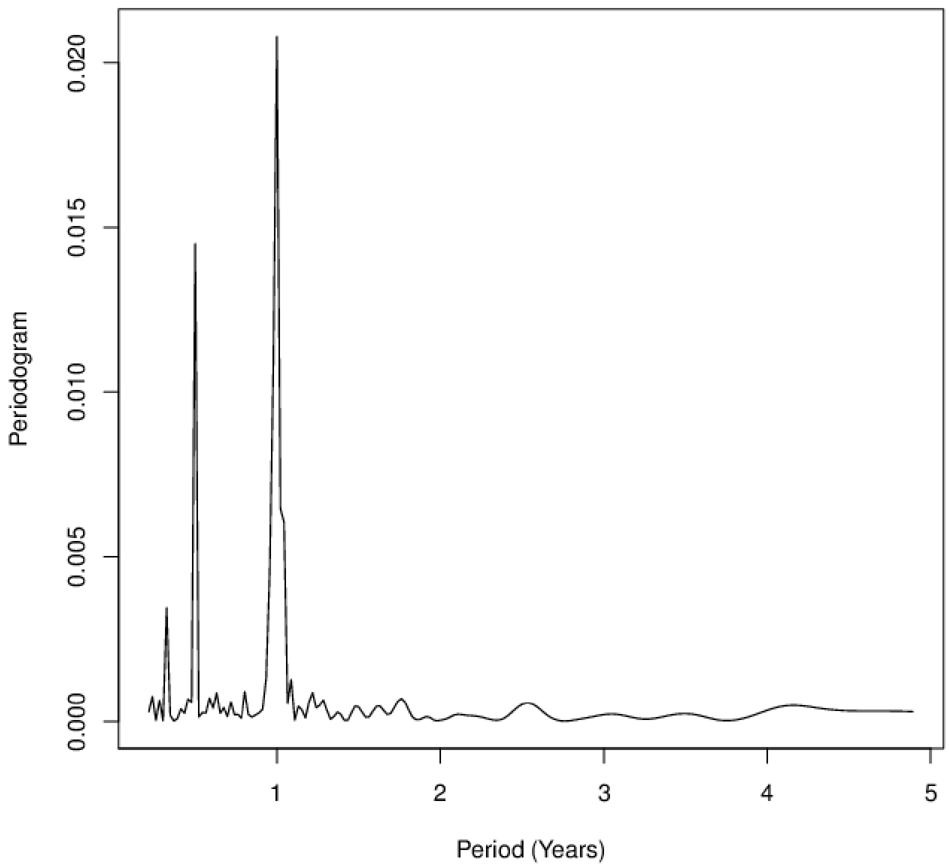

Figure 13. Lomb-Scargle periodogram of all fire counts across Côte d’Ivoire for the period 1984-2014.

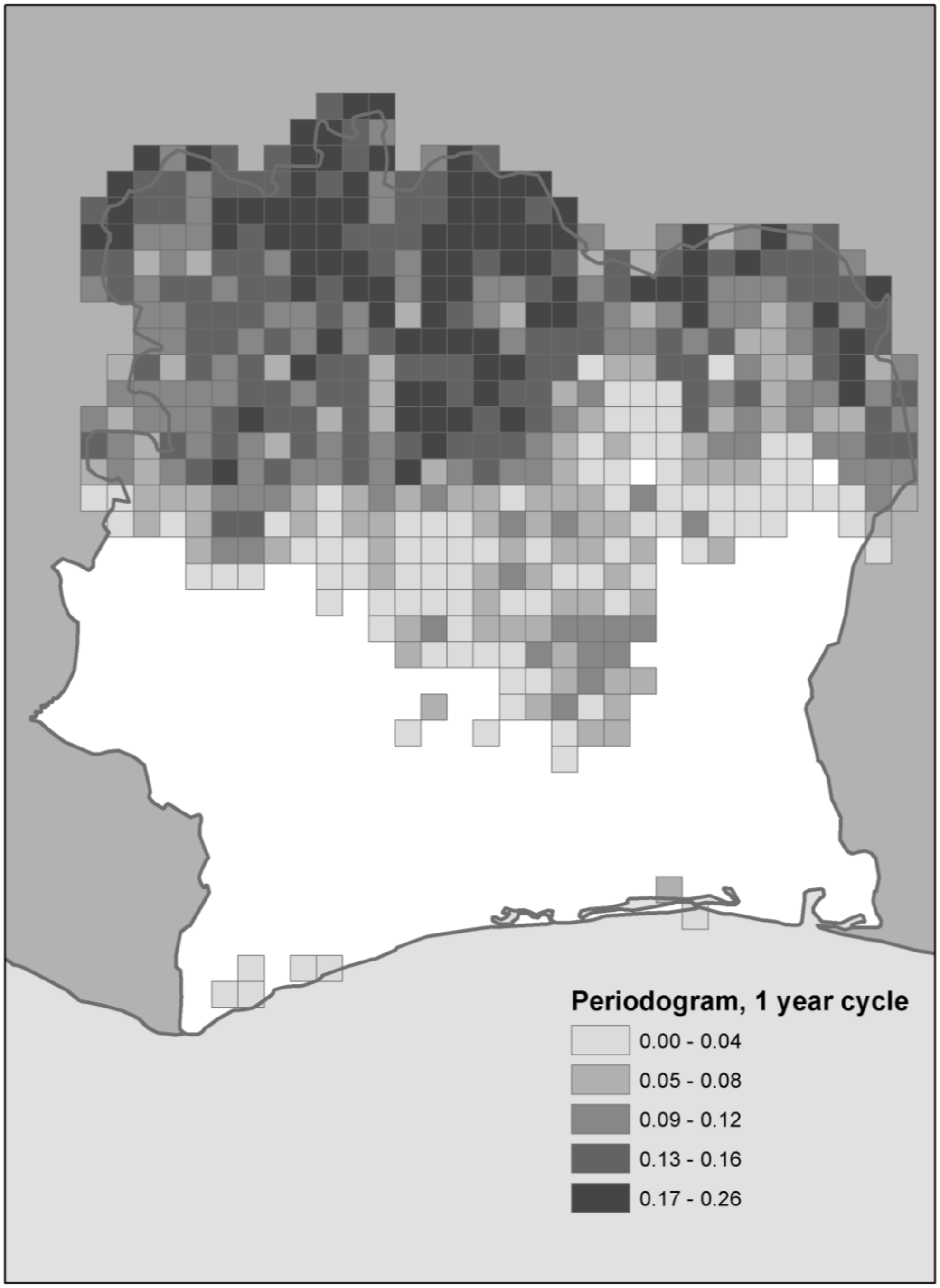

Figure 14. Spatial distribution of annual periodicity strength.

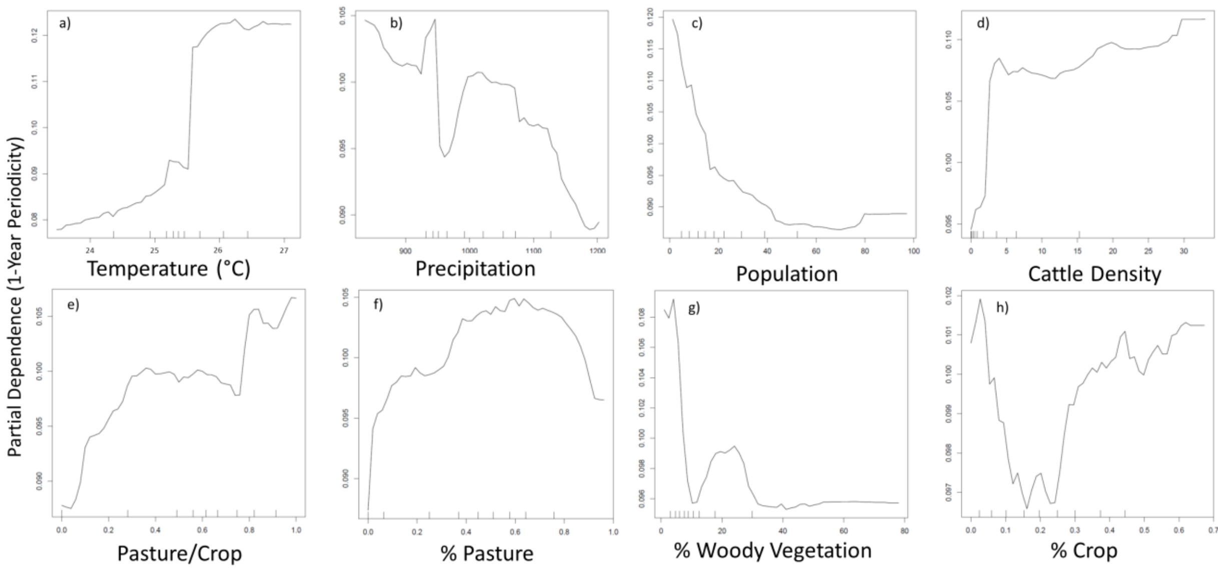

Figure 15. Partial dependence of fire regularity on independent variables as estimated by a random forest model. Plots show, in order of decreasing importance, the marginal effect on the predicted day of year attributed to a) temperature, b) precipitation, c) population density, d) cattle density, e) proportion of agricultural land in pasture, f) % pasture, g) % woody vegetation cover, and h) % cropland.

Table 4. Types of error in active fire detections and error rate.

Error Type	**Error Number**	**Error Rate**
Building or settlement	2	0.5%
Cloud	18	4.5%
Oversaturation	2	0.5%
Fully Saturated	2	0.5%
Impulse Noise (Bit-flip)	1	0.25%
Total Errors	**25**	**6.25%**
No Error	**400**	**93.75%**

Chapter 5. Discussion

5.1. Fire seasonality over time and space

The dominant feature of the fire regime of Côte d'Ivoire lies at the transition between the southern forest and northern savanna systems. The transition, rather than representing a smooth gradient from little fire to high fire density, appears as a rather sharp transition that is manifest as both an increase in fire density and a shift in seasonality. Once the transition is crossed, however, spatial heterogeneity in multiple directions is observed. This heterogeneity suggests that the fire regime is controlled by factors other than the dominant north-south climate gradient.

The spatial pattern of fire regularity I report matches the patterns found in an analysis of 12-month autocorrelation of MODIS active fire detections (Giglio et al., 2006). A pattern of high regularity in the north, as well as a pocket of high regularity in the Guinean savanna near the center of the country, was observed. In contrast, an area of low regularity is seen in the east. The same study reported broad patterns of peak fire activity that resemble my findings. Fire peaks later in the fire year to the south and fire density generally increases to the north. This pattern can probably be explained by the practice of shifting cultivation of crops in the southern forests, which requires fire set at the end of the dry season (de Rouw, 1994). My analysis reveals new, finer-scale patterns in the northern Sudanian savanna for fire regularity and seasonality.

The increasing fire density with 2-year precipitation and PDSI is best explained by increasing fuel production associated with wet years before a burn season. Particularly dry conditions can also contribute to higher fire density.

Interannual variability is clearly apparent in the fire seasonality and fire density data. Variability in the fire season has been reported previously in Africa (Cooke et al., 1996). However, I do not identify a linear trend in countrywide timing of fire peak. This finding does not support the hypothesized change in fire seasonality due to increasing pastoralism across Côte d'Ivoire over the past 30 years. However, the relationships revealed here between cattle density, pasture, and fire activity suggest that such a trend is likely to occur if pastoralist activity continued to increase across broad scales. Below, I explore the effects of agriculture, focusing primarily on cattle grazing and the fire regime.

5.2. Fire Seasonality and Climate

That the characteristics of fire in Côte d'Ivoire are most strongly related to climate is not surprising. However, the relationships between fire and climate revealed in this study show trends that are unexpected within current paradigms in the fire literature. Increasing temperature, a phenomenon usually associated with fire risk, is shown here to be associated with declining fire density. This unusual relationship is probably related to the association of higher temperatures with higher rainfall in the climate datasets. High temperatures are also related to later fires and greater regularity of fire. A steep increase in fire regularity at approximately 25°C matches the north-south temperature gradient in Côte d'Ivoire. However, the north-south gradient runs counter to the observed shift to a later fire peak, suggesting that the heterogeneity in the fire regime within the savanna ecosystem also plays a role in these patterns.

While the relationship between temperature and fire regimes appears to be complex, the role of precipitation follows the trends of fire from south to north more directly. Fires become later, less regular, and less dense from south to north, and precipitation declines along the same direction. The direction of relationships between fire and precipitation match this gradient.

The power of PDSI in the modeling of fire regimes has been noted previously (Keeley, 2004). This metric measures drought through a measure of climate anomaly based on temperature, precipitation, and several other factors. My results show that, in years with particularly low mean PDSI indicating persistent drought, fire density increases and the fire peak shifts later in the year. I hypothesize that this trend can be explained by two factors. First, drought during the growing season results in a paucity of fuel available to burn, reducing the number of potential fires in the early dry season. However, as woody vegetation desiccates during extreme dry years, the number of fires increases and the density of fire eventually overtakes that of years that are less dry.

5.3. Fire Seasonality and Land Use/Land Cover

This study was motivated by interest in the effects of increasing pastoralism on the timing of fire. In this study, I confirm the importance of cattle grazing on fire regimes and reveal the aspects of fire most affected by grazing. Cattle density appears as the most important non-climate variable in predicting fire density, the second most important in fire periodicity, and also shows importance in the fire seasonality model. High cattle densities are associated with greater fire density and fire regularity in my study, which I argue is a product of the human management of rangelands for cattle production (Bassett et al., 2003). The relationship between cattle density and the time of fire peak is more complex, though the timing of fire peak cuts notably lower at high densities. This dip can be attributed to herders setting early fires to encourage the “green pick” (Bassett et al., 2003; Kull and Laris, 2009). Similar trends are revealed between percent pasture cover and the fire regime, lending additional strength to these conclusions.

Crop cultivation represents a second significant human activity with the potential to influence fire regimes. In contrast to previous findings showing declining burned area as a result of cropland expansion (Andela and van der Werf, 2014), my results suggest that crop cultivation is not important in relation to fire density, and that fire density increases somewhat in areas where the percentage of croplands is high. This could be because cropland is most prominent in the central north of Côte d’Ivoire and usually occurs in areas where other land cover types are present, as indicated by the maximum percent cover of about 70%. The fire signal could be associated with those other land cover types. The trend, however, is likely also related to the common practice of using fire for crop land preparation (Laris, 2002). The MODIS burned area product used elsewhere may fail to detect the effect of small fires in croplands.

The relationship of fire with population in Côte d'Ivoire is complex. Fire density and fire seasonality reach a minimum at intermediate population density values, while fire regularity declines directly with increasing population. Several factors could explain the relationship between fire density and population. First, protected areas where people are excluded from the landscape may experience higher rates of burning (Archibald, Scholes, et al., 2010; Grégoire and Simonetti, 2010), although this is not always the case (Palumbo, Grégoire, Simonetti, and Punga, 2011). Second, high fire densities may occur in locations with low population density because many extensive agricultural systems, herding and shifting agriculture in particular, make use of fire (Bassett et al., 2003). As population density increases, the danger presented by fire to property increases as well, resulting in fewer, earlier fires to act as fire breaks against later fires (Laris, 2002). In southern Africa, the opposite trend has been described, with increasing early season fires in high population density settlements (Archibald, Scholes, et al., 2010).

Woody vegetation shows a particularly strong positive correlation with fire peak day of year. I suggest that this may be a signal produced by differing land management strategies in grasslands and forests. In forests, shifting cultivation is common and relies on late burning at intervals as long as 15 years. In contrast, grasslands are burned more frequently and earlier in the dry season to promote grass regrowth. My observations of the effect of woody vegetation cover on fire density and seasonality match these practices.

5.4. Fire Regularity

Fire regularity has been hypothesized to represent a signal of the “humanization” of fire regimes (Laris et al., 2015; Laris, 2011, 2013). My results complicate this idea. In my model of fire regularity, temperature and precipitation show the greatest importance, outweighing the influence of human population and land use, though only slightly so. In addition, increasing population density is associated with lower fire regularity. Furthermore, the map of fire regularity shows only a slight decline in fire regularity within Comoé National Park compared to surrounding areas, despite a relative lack of human management. These results suggest that climatic factors may still play a primary role in determining where fire is most regular.

The human role in fire regimes is clear in my seasonality model. Fire regularity decreases with increasing population, but increases sharply where cattle are present and where the proportion of pasture substantially outweighs the proportion of cropland. However, the extent to which humans modify these regimes through their activities or to which their activities are modified by climate is unclear. Given the importance of climate in my model, I suggest that it is not appropriate to consider fire regularity a unique hallmark of human activity.

5.5. Limitations and Uncertainties

The percentage of variability explained in the models presented here is in line with previous attempts to model fire activity (Archibald, Nickless, et al., 2010; Keeley, 2004). In particular, the model of fire regularity shows strong explanation of the variance in the data. However, a large degree of uncertainty remains, particularly in the fire density and fire peak models. The relatively lower percentage of variability explained by the yearly model suggests that there may be other variables of importance to interannual variability in fire seasonality that have not been captured here. However, limitations of the datasets used may also affect the explanatory power of the models.

The input data used presents one area source of uncertainty. For instance, the authors note that the FAOSTAT pasture data used to produce pasture percent cover data is ambiguous, especially in the differentiation between forest, shrub and grassland where grazing occurs. In addition, they find that the greatest uncertainty in crop and pasture cover occurs in the Sahelo-Sudan region of West Africa (Ramankutty et al., 2008).

While cattle density data is an important predictor in my analysis, its ability to adequately describe the distribution of cattle in Côte d'Ivoire is limited by several factors. Changes in cattle density and distribution over years and between years commonly occurs in Côte d'Ivoire, particularly in relation to the practice of seasonal transhumance common among herders in the country (Bassett and Turner, 2006). Changing land use and land tenure, farmer-herder conflict, and the distribution of tse-tse flies also affect cattle densities, but these factors are not explicitly considered in the cattle distribution data used.

Finally, the land use/land cover indicators I use represent a static snapshot of the distribution of these elements, while the climate variables were allowed to vary over time in the fire density and fire seasonality models. This reduces the comparability of the climate and land use data. Regardless, I make use of the best available data for these indicators, following the approach of similar studies (Andela and van der Werf, 2014; Archibald et al., 2009; Archibald, Scholes, et al., 2010).

The active fire dataset I have created possess limitations itself. The properties of remotely sensed data can influence detected fire regimes (Freeborn, Cochrane, and Wooster, 2014), and active fire detections in particular are sensitive to bias caused by the timing of satellite overpass (Giglio, 2007). In this study, the time of satellite overpass limits fire detections to fires that burn at approximately 10 AM. Fires in northern hemisphere Africa are characterized by diurnal patterns specific to ecosystem type. Fire detections derived from geostationary satellite images show fire counts peaking at or after

12PM, although open and sparse grasslands show peaks in mid-morning and late afternoon instead (Roberts et al., 2009). My data may therefore overestimate fire in open grasslands compared to other land cover types. Additionally, various fire management objectives, such as fire break creation or crop field cleaning, may require that fire be set at different times of day, adding additional complexity to diurnal patterns of fire because of human management. These dynamics are not captured by my analysis.

The choice of grid cell size may have contributed to the low predictive power of the model as well. While a grid cell size of 20km allows for fine scale resolution of the data, only a few fires were captured in each observation. This may have increased the noise to signal ratio of the data because of the degree of chance involved with such low counts. While this study context was different from that reported here, Archibald et al. (2009) found that a 100km grid cell was optimal for a study of burned areas detected with MODIS. Nevertheless, the grid cell size I use provides an acceptable balance between spatial resolution and resolution of fire activity.

Finally, the use of random forest models in this study presents both valuable insight and challenges. Random forests, by their nature, incorporate variable interactions through the relative location of the branches of the regression tree. This characteristic gives random forests strong predictive power, but it also produces results that are more difficult to interpret. The partial plots presented here are designed to show the influence of one variable on the regression outcome, at the cost of ignoring variable interactions. Furthermore, while the variable importance as measured by percentage increase in mean square error provides some indication of the value of each input variable, this does not provide the clarity by tests of significance in linear models. It is therefore difficult to know just how much a given relationship “matters.”

5.6. Fire Seasonality, Change, and the Burn Center Narrative

The results of this analysis reveal important patterns and relationships in the fire regimes of Côte d'Ivoire. Specifically, my results illustrate that the effects of climate and land use on fire are intertwined in complex ways. Disentangling these effects is a significant challenge when there may be reinforcing relationships between climate, fire, and land use. The findings presented here show that livestock density and land use predict the regularity of fire with similar accuracy as climate variables. These patterns are important for land managers and for our understanding of the role of West Afircan fire in global change.

Humans demonstrate a unique capacity to alter the environment. The vast majority of fire ignitions in Africa can be traced to human sources. However, decisions about the timing of those ignitions are often made with explicit reference to climate and the growing season (Laris et al., 2015). Furthermore, the possibility of regular fire in West Africa is constrained to the north and south by rainfall. It is perhaps more productive, then, to see fire as a component of a human-natural coupled system in which both humans and climate play a role in an integrated manner. Thus, fire regimes may depend as much on the motivations of pastoralists moving to better pastures as on anomalies in rainfall or temperature. As I conceive it, this relationship articulates in such a way that a change in one will alter the effects of the other in respect to fire seasonality. When this view is taken, the question becomes not only how does land use influence fire, but *through which mechanism and to what degree* do fire, climate, and land use influence each other.

The results presented here point to one avenue through which these mechanisms may be investigated. By dissecting different aspects of the fire regime and their correlation to human activities, we may gain insight into the linkages among these elements and climate. I show that human activity across Côte d'Ivoire is strongly linked to fire regimes in ways that are specific to each aspect of the fire regime. This finding is not entirely new. Differing management has been shown to influence the spatial distribution and seasonal timing of fire, but not the total area burned, in a South African National Park, for instance (van Wilgen, Govender, Biggs, Ntsala, and Funda, 2004).

The burn center narrative as well as humanized perspectives of fire suggest that humans wield powerful control over fire regimes across Africa. My results suggest that human activities do influence the characteristics of fire and point to the ways in which these activities exert an effect. In particular, I show that cattle grazing is associated with more, earlier, and more regular fires. Increasing cattle densities could drive substantial changes in the fire regimes in some areas of Côte d'Ivoire. My results show an inhibitory effect of woody vegetation on fire density, and a growing interest in tree crops in Côte d'Ivoire could help push some areas from savanna to forest.

The effect of these agricultural trends could result in earlier or less intense fires in some areas of Côte d'Ivoire, but their effects would be antagonistic. At the same time, pastoralists must compete with expanding crop production as well (Andela and van der Werf, 2014). As these competing forces play out, a detailed understanding of their effects on fire is critical for land management and predictions about impacts on climate change. As interest in carbon sequestration in savannas grows (Bradstock et al., 2012; Neely et al., 2009; Wiedinmyer and Hurteau, 2010; Woodfine, 2009), the results of our study point to the potential impact of various management strategies on fire regimes and livelihoods. My results, however, also caution against broad assumptions about such effects due to spatial heterogeneity in fire regime characteristics and the interrelationship between humans, climate, and fire.

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